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Interaction Effects of Iron Ash and Steel Fibers on Concrete Strength Performance

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ABSTRACT

This study examines the mechanical performance of concrete incorporating iron ash (IAC) as a partial cement replacement and steel fibers (SFC) as reinforcement, with particular emphasis on the individual and combined effects of these additions on compressive and flexural strength. Concrete mixtures were prepared using iron ash contents of 5%, 10%, and 20% by weight of cement, and steel fiber dosages of 0.25%, 0.50%, and 0.75% by volume, and were tested after 28 days of curing. The results indicate that the inclusion of iron ash leads to a moderate improvement in compressive strength, attributed to its pozzolanic reactivity and its role in enhancing matrix densification. The incorporation of steel fibers significantly enhances compressive strength and, more prominently, improves flexural strength through crack-bridging mechanisms and increased post-cracking energy absorption capacity. The results of the two-way ANOVA reveal that neither iron ash nor steel fibers individually exert a statistically significant effect on compressive strength, and no significant interaction effect between the two variables is observed. In contrast, steel fiber content exhibits a strong and statistically significant influence on flexural strength. Furthermore, a moderate interaction effect between iron ash and steel fibers suggests improved interfacial bonding between the fiber and matrix when both materials are used concurrently. Overall, these findings demonstrate that steel fibers play a dominant role in enhancing tensile-related performance, whereas iron ash provides supplementary benefits, particularly when used in combination with fiber reinforcement.

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1. INTRODUCTION

Concrete remains the predominant material in structural applications due to its high compressive strength and versatility. However, the production of Ordinary Portland Cement (OPC) is a major contributor to global CO_2 emissions, accounting for approximately 7% of industrial greenhouse gas output (Habert et al., 2020; Nodehi & Taghvaee, 2022). This environmental impact has driven increasing interest in the use of Supplementary Cementitious Materials (SCMs), particularly those derived from industrial by-products, as partial replacements for cement to support more sustainable construction practices (Cheng et al., 2023; Corbu et al., 2023). Iron ash, a by-product of metal and steel manufacturing processes, contains reactive constituents such as Fe_2O_3, CaO, and SiO_2, enabling it to function as both a pozzolanic material and a micro-filler when incorporated into concrete (Kaplan et al., 2021). Previous studies have demonstrated that the inclusion of iron ash contributes to pore structure refinement and promotes additional calcium silicate hydrate (C–S–H) formation, thereby enhancing mechanical strength and reducing permeability (Ramirez et al., 2023; Yang et al., 2022; Ulucan et al., 2024). Furthermore, the utilization of such industrial waste materials supports resource efficiency and aligns with circular economy principles in infrastructure development (Deinert & Schmalenberger, 2024).

In addition to the use of SCMs, the incorporation of steel fibers has been widely reported to enhance the mechanical performance of concrete. Steel fibers act to bridge microcracks, improve post-cracking resistance, and increase energy absorption capacity, thereby reducing brittleness and enhancing ductility (Tripathi & Mishra, 2024). Previous studies indicate that steel fiber dosages in the range of 0.5% to 1.5% by volume can significantly improve flexural and tensile strength, while yielding comparatively limited gains in compressive strength (X. H. Wang et al., 2024). Recent studies have also investigated the combined incorporation of iron ash and steel fibers. Synergistic effects have been reported, wherein iron ash contributes to matrix densification, while steel fibers enhance crack resistance, collectively leading to improved structural performance (Hafez et al., 2019). Nevertheless, the extent of these improvements is highly dependent on appropriate mixture proportions, as excessive cement replacement may adversely affect mechanical properties (Aderinto et al., 2024).

The application of two-way analysis of variance (ANOVA) is essential for evaluating the mechanical performance of concrete incorporating iron ash and steel fibers. This statistical approach enables the assessment of the individual and combined effects of two independent variables—namely, iron ash content and steel fiber volume fraction—on dependent variables such as compressive and flexural strength. Furthermore, two-way ANOVA facilitates the identification of potential interaction effects between these variables, which is critical for optimizing mixture design and improving overall material performance (Hama et al., 2024). Previous studies have highlighted the effectiveness of two-way analysis of variance (ANOVA) in analyzing complex datasets, particularly where interactions between variables may reveal patterns that are not captured by single-factor analyses. This approach enhances statistical power through efficient variance partitioning, thereby improving the reliability of results when evaluating the influence of multiple factors (Hama et al., 2024). Moreover, its applicability has been demonstrated across various domains; in concrete research, for instance, it enables the identification of both the main and interaction effects of independent variables on strength and durability under varying conditions (R. Wang et al., 2019).

In the context of sustainable concrete development, the integration of mechanical property assessment with two-way ANOVA provides a robust framework for evaluating the synergistic effects of iron ash and steel fibers. The combined use of these materials has the potential to enhance overall performance while enabling rigorous statistical validation. Existing studies suggest that two-way ANOVA can effectively distinguish whether observed improvements arise from true interaction effects rather than simple additive contributions (Hama et al., 2024; Neamat & Hassan, 2021). Accordingly, this study employs two-way ANOVA to systematically investigate the individual and interactive effects of iron ash and steel fiber

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incorporation on the mechanical properties of concrete. By doing so, it aims to provide a more comprehensive understanding of their coupled behavior and to inform optimized mixture designs that support sustainable construction practices with reduced environmental impact.

2. LITERATURE REVIEW

Iron ash has attracted increasing attention as a supplementary cementitious material (SCM) due to its pozzolanic reactivity and its potential to reduce cement consumption, thereby contributing to more sustainable construction practices. The partial replacement of ordinary Portland cement (OPC) with 10–20% iron ash has been reported to enhance compressive strength by approximately 10–15% at 28 days, primarily attributed to its filler effect and the resulting microstructural densification (Nadir et al., 2022). In addition, studies employing X-ray diffraction (XRD) and scanning electron microscopy (SEM) have demonstrated that fine iron ash particles promote the formation of calcium silicate hydrate (C–S–H), which plays a critical role in long-term strength development (Nadir et al., 2022).

Further investigations have shown that the incorporation of iron ash derived from the metal casting industry at replacement levels of 10–20% can reduce porosity and improve sulfate resistance compared to conventional concrete mixtures (Nadir et al., 2022; Chen et al., 2023). These findings are consistent with previous studies indicating that iron-rich industrial by-products contribute to pore refinement and enhanced durability under aggressive environmental conditions, thereby supporting the effective use of iron ash within this substitution range (Widjajakusuma et al., 2022). Collectively, these results highlight the viability of iron ash as a partial cement replacement that balances mechanical performance with sustainability considerations. Steel fibers are widely acknowledged for their effectiveness in enhancing the mechanical behavior of concrete, particularly in improving toughness and crack resistance. The incorporation of hooked-end steel fibers at approximately 1% by volume has been shown to significantly increase flexural strength and energy absorption capacity, primarily due to improved crack-bridging mechanisms and stress transfer across microcracks (Citra et al., 2023). Moreover, studies have reported that increasing fiber volume fractions from 0% to 1.5% results in consistent improvements in splitting tensile and flexural strength, whereas the influence on compressive strength remains relatively moderate (Zhang et al., 2022).

Furthermore, steel fibers have been shown to enhance the ductility of concrete, thereby improving its structural resilience, particularly in applications subjected to cyclic and impact loading (Kassa et al., 2019; Nguyen, 2020). Prabagar et al. (2022) further emphasized the critical role of steel fibers in ensuring durability and structural integrity in seismic- and fatigue-sensitive systems, which are increasingly relevant in modern construction practices. Collectively, these studies support the premise that the incorporation of steel fibers not only improves mechanical performance but also satisfies the requirements of high-performance concrete applications. A growing body of research has investigated the synergistic effects of combining iron ash with steel fibers to simultaneously achieve sustainability and enhanced mechanical performance. For example, Ma et al. (2022) reported that concrete mixtures incorporating 15% iron ash and 1% steel fibers exhibited a significant improvement in flexural strength compared to conventional concrete, highlighting the benefits of hybrid material utilization. Microstructural analyses further revealed a denser cementitious matrix and improved interfacial bonding between fibers and the surrounding matrix, contributing to enhanced mechanical behavior.

Similarly, Chen et al. (2023) demonstrated that mixtures containing 10% iron ash and 0.75% steel fibers exhibited superior early-age crack resistance and improved thermal stability under fluctuating temperature conditions. These findings are consistent with prior studies indicating that hybrid systems can effectively enhance both stiffness and toughness of concrete. Nevertheless, the overall performance of such

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composites remains highly dependent on optimized fiber distribution and matrix cohesiveness, underscoring the importance of careful mixture design (Duan et al., 2020). The application of two-way analysis of variance (ANOVA) in evaluating concrete formulations incorporating iron ash and steel fibers represents a robust statistical approach for quantifying their individual and interactive effects on mechanical performance. This method enables the simultaneous assessment of two independent variables—namely, iron ash content and steel fiber volume fraction—on dependent variables such as compressive and flexural strength, while explicitly accounting for potential interaction effects (Kumara et al., 2023; Imran et al., 2023).

Through two-way ANOVA, both main and interaction effects can be systematically examined. The main effects describe the independent influence of variations in iron ash content or steel fiber dosage on mechanical performance, whereas the interaction effect determines whether the influence of one variable depends on the level of the other (Husain & Abas, 2015). This analytical framework is particularly relevant in the context of hybrid concrete systems, where synergistic interactions between supplementary materials and fiber reinforcement may lead to enhanced material properties (Cordeiro et al., 2019). For example, two-way ANOVA can be employed to evaluate concrete mixtures with varying iron ash contents (5%, 10%, and 20%) and steel fiber volume fractions (0.25%, 0.50%, and 0.75%), with mechanical properties assessed at specified curing ages (Hama et al., 2024). Statistical software packages, such as SPSS, facilitate the analysis by generating interaction plots and quantitative outputs that aid in interpreting the relationships between variables (Chandio et al., 2020). Overall, the integration of two-way ANOVA into the analysis of concrete incorporating iron ash and steel fibers enhances the rigor and reliability of experimental findings. Moreover, it supports the identification of optimal mixture designs that balance mechanical performance and sustainability, thereby contributing to the advancement of eco-efficient concrete technologies (Ketkukah et al., 2022).

Despite the growing body of research on the use of iron ash as a supplementary cementitious material and the incorporation of steel fibers as reinforcement, studies that systematically evaluate their combined effects using rigorous statistical approaches remain limited. In particular, the interaction between iron ash content and steel fiber volume fraction has not been comprehensively quantified, and existing findings often report inconsistent trends regarding their influence on compressive and flexural performance. Furthermore, while several studies have highlighted the individual benefits of these materials, the extent to which their combined application produces true synergistic effects—rather than merely additive contributions—has yet to be clearly established. To address these gaps, the present study investigates the mechanical performance of concrete incorporating varying proportions of iron ash and steel fibers, with a specific focus on their interaction effects. A two-way analysis of variance (ANOVA) is employed to systematically evaluate both the main and interaction effects of these variables on compressive and flexural strength. This approach enables a more rigorous assessment of material behavior and provides new insights into optimizing mixture design. The findings of this study are expected to contribute to the development of high-performance and sustainable concrete by clarifying the role of hybrid material systems in enhancing mechanical properties.

3. RESEARCH METHODOLOGY

This study was conducted through a structured experimental program designed to evaluate the individual and combined effects of iron ash and steel fibers on the mechanical performance of concrete. The experimental procedure consisted of four main stages: (1) material characterization and preparation, (2) concrete mix design based on predefined variables, (3) specimen casting and curing, and (4) mechanical testing followed by statistical analysis and interpretation of the results. The overall methodological framework is illustrated in Fig. 1, highlighting the sequential and controlled nature of the experimental workflow.

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3.1 Materials

The materials used in this study were selected based on their engineering relevance and local availability to ensure practical applicability in real construction scenarios. All materials were sourced locally from regions with relatively consistent geological and industrial characteristics to maintain uniformity throughout the experimental program.

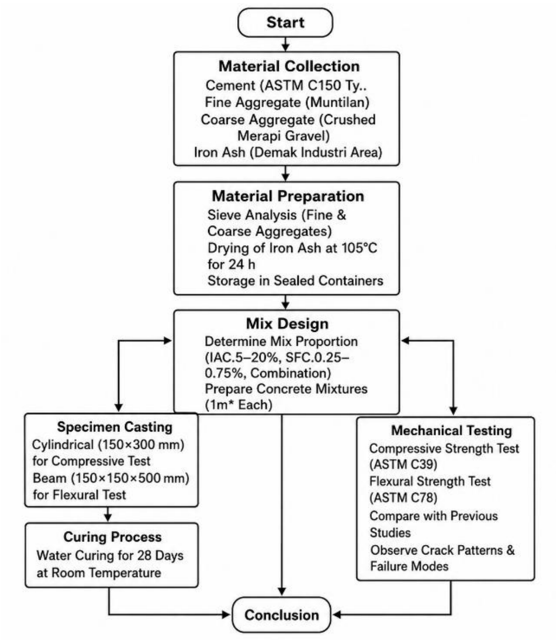

Fig. 1. Research Methodology Flowchart

3.1.1 Fine Aggregate (Sand)

The fine aggregate was obtained from Muntilan, located on the slopes of Mount Merapi, where volcanic processes produce angular sand particles with favorable interlocking characteristics. This angularity enhances shear resistance and contributes to the overall stiffness of the concrete matrix. Additionally, the low clay and silt content minimizes interference with cement hydration and microstructural development. The sand complied with the grading and cleanliness requirements specified in ASTM C33 and SNI 03-2834-2000, ensuring consistent compaction behavior and adequate paste–aggregate bonding.

3.1.2 Coarse Aggregate (Crushed Stone)

The Coarse Aggregate, also sourced from the Merapi region, consisted of crushed igneous rock with a rough surface texture that enhances mechanical interlock and strengthens the bond between the aggregate and cement paste. A nominal maximum particle size of 20 mm was selected, as it is commonly used in reinforced concrete applications and provides an optimal balance between packing density and void reduction.

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3.1.3 Cement

Ordinary Portland Cement (OPC) Type I was used due to its well-established performance, stable hydration characteristics, and compatibility with supplementary cementitious materials. Its relatively high tricalcium silicate (C_3S) content supports early-age strength development, while dicalcium silicate (C_2S) contributes to long-term strength and durability.

3.1.4 Iron Ash as a Supplementary Cementitious Material

The iron ash used in this study is a fine inorganic by-product generated from steel manufacturing processes. Its high Fe_2O_3 content contributes to pozzolanic reactivity, particularly through interactions with calcium hydroxide released during cement hydration. This reaction facilitates the formation of secondary calcium silicate hydrate (C–S–H), leading to improved matrix densification. However, its effectiveness is strongly influenced by particle size distribution, replacement level, and curing conditions. Prior to use, the iron ash was oven-dried to eliminate residual moisture and sieved to ensure uniform particle fineness. This treatment improved its dispersion within the cementitious matrix and minimized the formation of weak interfacial transition zones (ITZ).

3.1.5 Steel Fibers

Hooked-end steel fibers were incorporated to enhance post-cracking behavior, tensile performance, load redistribution capacity, and overall ductility of the concrete. The selected aspect ratio (L/d = 60) is widely recognized as effective in improving fiber anchorage, reducing pull-out, and increasing energy absorption under flexural loading.

3.2 Mix Design Strategy

The mix design was developed to achieve the target compressive strength for structural-grade concrete while maintaining adequate workability for fiber-reinforced mixtures. Iron ash was introduced as a partial replacement for cement at levels of 5%, 10%, and 20% by weight, whereas steel fibers were incorporated at volume fractions of 0.25%, 0.50%, and 0.75%. This experimental matrix enabled: the isolated evaluation of iron ash effects, the isolated evaluation of steel fiber effects, and the assessment of potential synergistic or antagonistic interactions between the two variables. The complete mix proportions are presented in Table 1. Adjustments were made to maintain a constant water-to-cementitious materials ratio, thereby minimizing the influence of workability as a confounding variable.

Table 1. Concrete Mix Proportions

Mix ID	Cement	Fine Aggregate	Coarse aggregate	Water	Iron Ash (% by weight of cement)		Steel Fiber (% by volume of concrete)	
	[kg/m3]	[kg/m3]	[kg/m3]	[kg/m3]	[%]	[kg/m3]	[%]	[kg/m3]
NC	286	1130	830	185	0	0	0	0
IAC05	286	1130	830	185	5	14	0	0
IAC10	286	1130	830	185	10	29	0	0
IAC20	286	1130	830	185	20	57	0	0
SFC0.25	286	1130	830	185	0	0	0.25	20
SFC0.50	286	1130	830	185	0	0	0.50	39
SFC0.75	286	1130	830	185	0	0	0.75	59
IAC05+SFC0.25	286	1130	830	185	5	14	0.25	20
IAC10+SFC0.50	286	1130	830	185	10	29	0.50	39
IAC20+SFC0.75	286	1130	830	185	20	57	0.75	59

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3.3 Specimen Preparation and Curing

All concrete mixtures were prepared using mechanical mixing and cast into standardized molds in accordance with established procedures. Compaction was performed using a mechanical vibrator to minimize entrapped air and internal voids. After 24 hours, the specimens were demolded and subsequently cured in water at a controlled temperature of 23 ± 2°C until the designated testing age of 28 days. This curing regime ensured consistent hydration conditions and enhanced the reproducibility of mechanical test results.

3.4 Mechanical Testing

Compressive strength tests were conducted on cylindrical specimens with dimensions of 150 mm × 300 mm in accordance with ASTM C39/C39M. The compressive strength was determined based on applied load and specimen geometry as expressed in Eq. (1):

$$f_c' = \frac{P}{A} \tag{1}$$

where P represents the maximum applied load, and A denotes the cross-sectional area of the specimen.

Flexural strength was evaluated using the third-point loading method in accordance with ASTM C78/C78M, which allows for the determination of the modulus of rupture. The flexural strength was calculated using Eq. (2):

$$f_r = \frac{PL}{bh^2} \tag{2}$$

where P is the maximum applied load, L is the span length, b is the specimen width and h is the specimen depth.

4. RESULT AND DISCUSSION

4.1 Concrete Compressive Strength Test Results

Compressive strength testing was conducted to evaluate the capacity of concrete to resist axial compressive loads. This property is strongly influenced by the quality of constituent materials, mixture proportions, curing conditions, and the incorporation of supplementary materials such as iron ash (IAC) and steel fibers (SFC). In this study, the concrete mixtures were designed to achieve a target compressive strength of 17 MPa. Iron ash was used as a partial cement replacement at levels of 5%, 10%, and 20% by weight, while steel fibers were incorporated at volume fractions of 0.25%, 0.50%, and 0.75%. Each mixture variation consisted of three cylindrical specimens (150 mm × 300 mm), which were tested after 28 days of curing. Fig. 2. presents the concrete compressive strength test.

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Fig. 2. Concrete Compressive Strength Test

Table 2 presents the compressive strength results for all mixtures, and Fig. 3 illustrates the average strength values.

Table 2. Compressive Strength Test Results

Mix ID		Compressive Strength (MPa)	Compressive Strength Average (MPa)
NC	1	19.25	19.63
	2	19.82	
	3	19.82	
IAC5	1	18.68	20.95
	2	21.51	
	3	22.65	
IAC10	1	19.82	20.38
	2	20.38	
	3	20.95	
IAC20	1	20.38	21.89
	2	20.95	
	3	24.35	
SFC0.25	1	23.21	24.91
	2	25.48	
	3	26.04	
SFC0.50	1	23.78	25.48
	2	25.48	
	3	27.18	
SFC0.75	1	22.65	25.48
	2	25.48	
	3	28.31	
IAC5+SFC0.25	1	20.38	21.51
	2	20.95	
	3	23.21	
IAC10+SFC0.50	1	21.51	22.08
	2	22.08	
	3	22.65	
IAC20+SFC0.75	1	22.08	22.65
	2	22.65	
	3	23.21	

The results shown in Fig. 3 indicate that the control mixture (normal concrete, NC) achieved an average compressive strength of 19.63 MPa. The incorporation of iron ash as a partial cement replacement resulted in a moderate enhancement in compressive strength. Specifically, mixtures containing 5%, 10%, and 20% IAC exhibited average strengths of 20.95 MPa, 20.38 MPa, and 21.89 MPa, respectively. This improvement can be attributed to the pozzolanic reactivity of iron ash, which contributes to matrix densification and enhances bonding within the cementitious system. A more pronounced increase in compressive strength was observed with the addition of steel fibers. Mixtures incorporating 0.25%, 0.50%,

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and 0.75% SFC achieved compressive strengths of 24.91 MPa, 25.48 MPa, and 25.48 MPa, respectively. These findings confirm the effectiveness of steel fibers in improving crack resistance and facilitating stress transfer across microcracks, thereby enhancing the overall load-bearing capacity of the concrete.

However, the combined incorporation of iron ash and steel fibers did not result in superior performance compared to mixtures containing steel fibers alone. Although the hybrid mixtures demonstrated improved compressive strength relative to the control concrete, their values remained slightly lower than those of the corresponding fiber-only mixtures. For example, the mixture containing 20% IAC and 0.75% SFC achieved a compressive strength of 22.65 MPa, compared to 25.48 MPa for the mixture with 0.75% SFC without iron ash. This observation suggests that the synergistic interaction between iron ash and steel fibers may not be fully optimized. Factors such as particle packing density, interfacial transition zone (ITZ) characteristics, and hydration kinetics may influence this behavior and warrant further investigation.

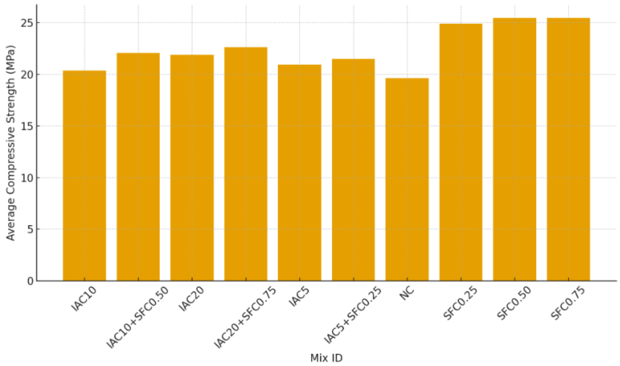

Fig. 3. Average Compressive Strength Graph

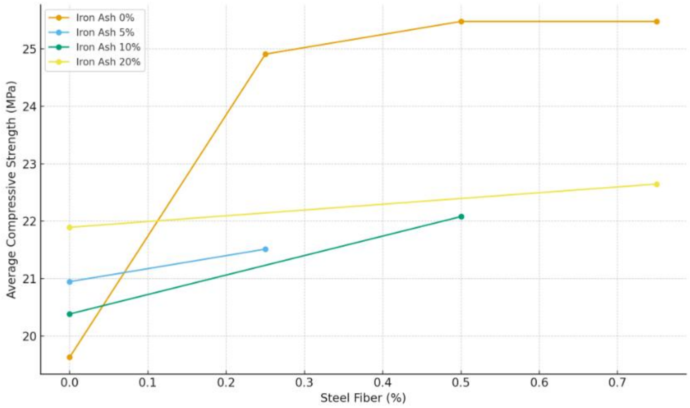

Fig. 4. Compressive Strength Response to Combined Variations of Iron Ash and Steel Fiber

Source: Author's own elaboration based on experimental data (2025)

Fig. 4 illustrates the compressive strength response of concrete mixtures subjected to combined variations in iron ash (IAC) replacement and steel fiber (SFC) content. The results demonstrate that the incorporation of steel fibers consistently enhances compressive strength across all levels of iron ash replacement. Mixtures containing steel fibers exhibit higher compressive strength than those incorporating

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iron ash alone, confirming the effectiveness of fibers in improving resistance to axial loading. However, the combined use of iron ash and steel fibers does not exceed the compressive strength achieved by fiber-reinforced mixtures without iron ash. Although iron ash contributes to microstructural densification through pozzolanic reactions, its benefits appear limited in hybrid systems. This suggests that the strengthening mechanism associated with steel fibers—particularly crack bridging and enhanced stress transfer—plays a more dominant role in compressive strength development, whereas the contribution of iron ash remains supplementary rather than synergistic for this property.

4.2 Two-Way ANOVA Analysis

To quantitatively assess the individual and combined effects of iron ash and steel fibers on compressive strength, a two-way analysis of variance (ANOVA) was performed as shown in Table 3.

Table 3. Two-Way ANOVA Results for the Effects of Iron Ash and Steel Fiber Content on Compressive Strength

Source of Variation	Sum of Squares	df	F-value	p-value	η^2 (Effect Size)	Interpretation
Iron Ash Content (IAC)	4.319	2	1.08	0.370	0.13 *(small)*	Iron ash replacement shows minimal influence on compressive strength when used alone.
Steel Fiber Content (SFC)	4.550	1	2.28	0.157	0.13 *(small)*	Steel fiber addition also does not significantly affect compressive strength by itself at the tested dosages.
Interaction (IAC × SFC)	1.101	2	0.28	0.764	0.03 *(very small)*	The combined use of iron ash and steel fiber does not produce a synergistic effect on compressive strength.
Error	23.979	12	-	-	-	-

The results indicate that variations in iron ash content (IAC level) do not exert a statistically significant effect on compressive strength ($F = 1.08$; $p = 0.370$). Similarly, although steel fiber incorporation shows a trend toward increased compressive strength, the effect is not statistically significant at the selected confidence level ($F = 2.28$; $p = 0.157$). Furthermore, the interaction between iron ash content and steel fiber dosage is not significant ($F = 0.28$; $p = 0.764$), indicating that the influence of steel fibers is largely independent of IAC levels. Nevertheless, the effect size ($\eta^2 \approx 0.13$) suggests that steel fiber incorporation provides a practically meaningful contribution to compressive performance, particularly in enhancing load-bearing capacity. This distinction between statistical significance and practical relevance underscores the importance of combining inferential and effect size analyses in evaluating material performance.

4.3 Flexural Strength Test Results

Flexural strength, commonly expressed as the modulus of rupture, represents the ability of concrete to resist bending stresses prior to failure. In this study, beam specimens with dimensions of 150 mm × 150 mm × 500 mm were tested after 28 days of curing. The complete results are presented in Table 4, while Fig. 5 illustrates the corresponding trends in average flexural strength.

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Fig. 5. Flexural Strength Test

Table 4. Flexural Strength Test Results

Mix ID		Flexural Strength (MPa)	Flexural Strength Average (MPa)
NC	1	5.33	5.69
	2	5.33	
	3	6.40	
IAC5	1	4.67	5.11
	2	5.20	
	3	5.47	
IAC10	1	4.67	4.98
	2	5.07	
	3	5.20	
IAC20	1	4.80	4.89
	2	4.93	
	3	4.93	
SFC0.25	1	5.20	5.42
	2	5.33	
	3	5.73	
SFC0.50	1	5.33	5.51
	2	5.47	
	3	5.73	
SFC0.75	1	5.47	5.82
	2	6.00	
	3	6.00	
IAC5+SFC0.25	1	5.33	5.56
	2	5.60	
	3	5.73	
IAC10+SFC0.50	1	5.60	5.64
	2	5.60	
	3	5.73	
IAC20+SFC0.75	1	5.73	6.13
	2	6.00	
	3	6.67	

The results in Fig. 6 shows that the highest flexural strength was achieved in the mixture containing 0.75% steel fibers (SFC0.75), with an average value of 5.82 MPa. This value exceeds that of the control mixture (5.69 MPa), demonstrating the significant contribution of steel fibers to flexural performance. This enhancement is primarily attributed to the crack-bridging capability of the fibers, which delays crack initiation and propagation, increases post-cracking ductility, and improves energy absorption capacity. In contrast, mixtures incorporating iron ash as the sole modification exhibit a reduction in flexural strength. This indicates that, while iron ash contributes to matrix densification, its effect is more beneficial under compressive loading than under tensile or flexural stresses. The reduced performance may be associated with the limited capacity of iron ash to resist tensile crack initiation and propagation.

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However, the combined incorporation of iron ash and steel fibers results in improved flexural strength (shown in Fig. 7) compared to mixtures containing iron ash alone. This suggests a partial synergistic effect, in which the pozzolanic activity of iron ash enhances matrix densification and improves fiber–matrix interfacial bonding. Consequently, the steel fibers can more effectively transfer stresses and control crack development under flexural loading. Overall, these findings indicate that steel fibers act as the primary contributor to flexural performance enhancement, whereas iron ash provides a secondary, supporting role that becomes more effective in the presence of fiber reinforcement. This interaction highlights the importance of optimizing material combinations to achieve balanced mechanical performance in advanced cementitious composites.

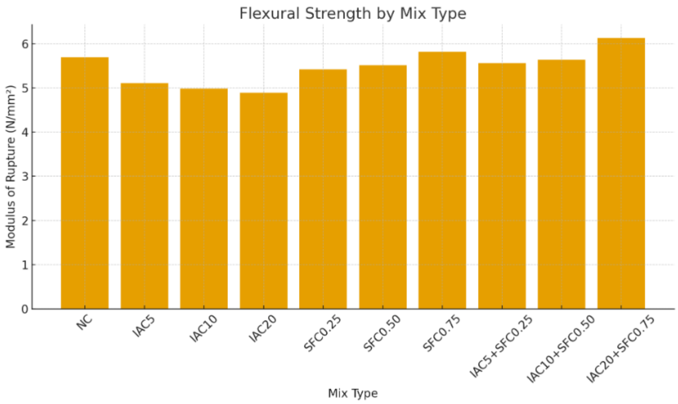

Fig. 6. Average Flexural Strength Graph

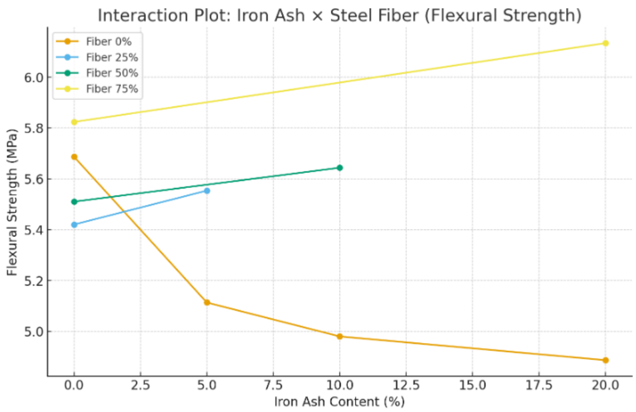

Fig. 7. Flexural Strength Response to Combined Variations of Iron Ash and Steel Fiber

The interaction plot in Fig. 7 indicates that mixtures without steel fibers exhibit a decline in flexural strength with increasing iron ash content, suggesting that iron ash alone is not effective in enhancing tensile crack resistance. In contrast, the incorporation of steel fibers leads to a consistent improvement in flexural strength, with greater enhancements observed at higher fiber volume fractions. For mixtures containing 0.25% and 0.50% steel fibers, flexural strength increases moderately with increasing iron ash content, indicating improved fiber–matrix interfacial bonding due to matrix densification associated with the pozzolanic activity of iron ash. The mixture with 0.75% steel fibers demonstrates the highest flexural

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strength across all levels of iron ash, suggesting a synergistic interaction in which iron ash enhances the effectiveness of steel fibers in bridging cracks and resisting flexural stresses. Overall, these results confirm that steel fiber content is the dominant factor governing flexural performance, while iron ash provides a beneficial contribution primarily when used in combination with fiber reinforcement.

4.4 Two-Way ANOVA Analysis

To quantitatively evaluate the individual and combined effects of iron ash replacement and steel fiber addition on flexural strength, a two-way analysis of variance (ANOVA) with interaction was performed. Iron ash content was defined as Factor A (0–20% replacement), while steel fiber volume fraction was defined as Factor B (0–0.75% addition). The statistical results, including effect sizes (η^2), are summarized in Table 5.

Table 5. Two-Way ANOVA Results for the Effects of Iron Ash and Steel Fiber Content on Flexural Strength

Source of Variation	Sum of Squares	df	F-value	p-value	η^2 (Effect Size)	Interpretation
Iron Ash Content	0.0225	1	0.82	0.401	0.02 (small)	Minimal influence when used alone
Steel Fiber Content	0.8682	1	31.47	0.001	0.64 (large)	Major factor governing flexural strength
Interaction (A × B)	0.3003	1	10.89	0.016	0.22 (moderate)	Synergistic enhancement when combined
Error	0.1655	6	-	-	0.12	-

The analysis reveals that steel fiber content is the most influential factor affecting flexural strength, accounting for approximately 64% of the total variance ($\eta^2 = 0.64$). This substantial contribution is consistent with the role of steel fibers in bridging microcracks, enhancing post-cracking resistance, and improving stress redistribution within the cementitious matrix. In contrast, the effect of iron ash content alone is relatively minor and statistically non-significant ($p = 0.401$), indicating that iron ash does not significantly influence flexural performance when used independently. However, the interaction between iron ash and steel fibers is statistically significant ($p = 0.016$), with a moderate effect size ($\eta^2 = 0.22$). This result suggests that the beneficial influence of iron ash on flexural strength is contingent upon the presence of steel fibers.

The improvement can be attributed to matrix densification resulting from the pozzolanic activity of iron ash, which enhances fiber anchorage and interfacial bonding between the fibers and the surrounding matrix. Consequently, the contribution of iron ash is effectively activated and amplified in fiber-reinforced systems, supporting the concept of material synergy. These findings are consistent with previous studies reporting that mineral or metallic additives can enhance fiber–matrix adhesion and crack-arresting mechanisms when used in conjunction with steel fibers, while providing limited benefits in flexural performance when applied independently (Zhang et al., 2022). Therefore, the present results emphasize the importance of integrated material optimization rather than isolated modification of individual concrete constituents.

5. CONCLUSION

This study demonstrates that the incorporation of iron ash as a partial cement replacement provides a modest enhancement in compressive strength, with optimal performance observed at a 20% substitution level. This improvement is primarily attributed to the pozzolanic reactivity and micro-filling effect of iron ash, which contribute to matrix densification and microstructural refinement. In contrast, the inclusion of steel fibers exerts a more substantial influence on mechanical performance, particularly in flexural strength. The crack-

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bridging capability of the fibers effectively delays crack initiation and propagation, enhances post-cracking energy absorption, and improves overall ductility and bending resistance. The combined use of iron ash and steel fibers results in improved mechanical properties compared to mixtures incorporating iron ash alone; however, the hybrid mixtures do not surpass the performance of fiber-reinforced concrete without iron ash. This finding indicates that, although iron ash contributes to matrix enhancement, the mechanical performance is predominantly governed by the reinforcing action of steel fibers. The results of the two-way analysis of variance (ANOVA) further substantiate this conclusion, demonstrating that steel fiber content is the most influential factor affecting flexural strength, whereas iron ash alone exhibits a comparatively limited effect. Nevertheless, the presence of a moderate interaction effect suggests that matrix densification induced by iron ash can enhance fiber–matrix interfacial bonding, thereby improving the efficiency of fiber reinforcement. Overall, the findings confirm that iron ash is a viable supplementary cementitious material, particularly when used in conjunction with steel fibers. However, the full potential of this hybrid system has not yet been fully realized. Further optimization of mixture design—particularly with respect to fiber dosage, dispersion, and particle packing—is necessary to maximize synergistic interactions and achieve superior mechanical performance. These insights contribute to the advancement of sustainable and high-performance concrete technologies.

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7. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

8. AUTHORS' CONTRIBUTIONS

Purwanto contributed to the conceptualization, research design, supervision, data interpretation, manuscript drafting, and final approval of the manuscript. Trias Widorini contributed to the methodology, experimental planning, data analysis, and review of the manuscript. Hani Purwanti contributed to material preparation, laboratory testing, data collection, and validation of the experimental results. Ngudi Hari Crista contributed to specimen preparation, mechanical testing, and organization of the research data. Agus Muldiyanto contributed to statistical analysis, interpretation of the ANOVA results, and preparation of tables and figures. Aimmatul Husna contributed to literature review, manuscript editing, formatting, and reference checking. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

9. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

The authors declare that generative artificial intelligence (AI) tools may have been used solely to support language refinement during the preparation of this manuscript. Such tools were used only to improve grammar, sentence structure, clarity, and overall readability. All aspects of the research, including the study design, data collection, data extraction, analysis, interpretation of findings, and final academic decisions,

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were conducted, reviewed, and approved by the authors. The authors take full responsibility for the accuracy, integrity, originality, and scholarly content of this manuscript.

10. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The data and/or supplementary materials supporting the findings of this study are available from the corresponding author upon reasonable request, where applicable.

11. ETHICS STATEMENT

The authors declare that this study did not involve human participants or animal subjects. Where applicable, all procedures were conducted in accordance with relevant institutional guidelines, safety requirements, and ethical standards.

REFERENCES

Aderinto, G. E., Ikotun, J. O., Katte, V. Y., & Madirisha, M. M. (2024). Geopolymer cement in pavement applications: Bridging sustainability and performance, an in-depth review. *Sustainability, 16*(13), Article 5417. https://doi.org/10.3390/su16135417

Chandio, S., Memon, B. A., Oad, M., Chandio, F. A., & Memon, M. U. (2020). Effect of fly ash on the compressive strength of green concrete. *Engineering, Technology & Applied Science Research, 10*(3), 5728–5731. https://doi.org/10.48084/etasr.3499

Chen, R., Duan, Y., Yang, M., & Sun, J. (2023). Experimental investigations of the bond strength between iron tailing concrete and steel bars. *Structural Concrete, 25*(3), 1753–1764. https://doi.org/10.1002/suco.202200905

Cheng, H., Chen, P., Cao, S., & Li, Y. (2023). Stress–strain model of steel fibre-reinforced alkali-activated slag cementitious material after high-temperature exposure. *Journal of Building Engineering, 79*, Article 107743. https://doi.org/10.1016/j.jobe.2023.107743

Citra, S. Z. K., Wahyuni, W., Munawir, M., Vito, R. F., & Rais, T. I. (2023). Effect of mixing *Anadara granosa* shells ash and fly ash as a cement replacement on foamed concrete properties. *Key Engineering Materials, 943*, 233–240. https://doi.org/10.4028/p-77jq49

Corbu, O., Puskás, A., Dragomir, M. L., Har, N., & Toma, I.-O. (2023). Eco-innovative concrete for infrastructure obtained with alternative aggregates and a supplementary cementitious material (SCM). *Coatings, 13*(10), Article 1710. https://doi.org/10.3390/coatings13101710

Cordeiro, G. C., Andreão, P. V., & Tavares, L. M. (2019). Pozzolanic properties of ultrafine sugar cane bagasse ash produced by controlled burning. *Heliyon, 5*(10), Article e02566. https://doi.org/10.1016/j.heliyon.2019.e02566

Deinert, L., & Schmalenberger, A. (2024). Reuse of soils fertilized with ash as recycling derived fertilizer revealed strong stimulation of microbial communities involved in P mobilization in *Lolium perenne* rhizospheres. *Environments, 11*(3), Article 49. https://doi.org/10.3390/environments11030049

Duan, Y., Sun, J., Dun, C., Guo, Y., Ma, X., & Yang, M. (2020). Mix design and strength properties of full iron tailings concrete. *Journal of Physics: Conference Series, 1637*(1), Article 012028. https://doi.org/10.1088/1742-6596/1637/1/012028

https://doi.org/10.24191/mij.v7i1.11948

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment, 1*(11), 559–573. https://doi.org/10.1038/s43017-020-0093-3

Hafez, H., Cheung, W. M., Nagaratnam, B., & Kurda, R. (2019). A proposed performance-based approach for life cycle assessment of reinforced blended cement concrete. *Proceedings of the International Conference on Sustainable Construction Materials and Technologies, 3*, 50–61. https://doi.org/10.18552/2019/idscmt5135

Hama, S. M., Al-Ani, H. K. K., & Alfahdawi, I. H. (2024). ANOVA statistical analysis for determining the optimum contain of waste powders in concrete. *Salud, Ciencia y Tecnología – Serie de Conferencias, 3*, Article 852. https://doi.org/10.56294/sctconf2024852

Husain, A. H., & Abas, N. F. (2015). The mechanical performance of waste concrete ash as cement replacement materials in concrete. *Applied Mechanics and Materials, 747*, 234–237. https://doi.org/10.4028/www.scientific.net/amm.747.234

Imran, N. F., Hashim, N. H., Hasan, D., Radzi, A. S. M., & Harizan, M. T. (2023). Behaviour of normal concrete with sugarcane bagasse ash (ScBA) as partial cement replacement. *IOP Conference Series: Earth and Environmental Science, 1238*(1), Article 012016. https://doi.org/10.1088/1755-1315/1238/1/012016

Kaplan, G., Bayraktar, O. Y., Gholampour, A., Ozbakkaloglu, T., & Oz, H. O. (2021). Mechanical and durability properties of steel fiber-reinforced concrete containing coarse recycled concrete aggregate. *Structural Concrete, 22*(5), 2791–2812. https://doi.org/10.1002/suco.202100028

Kassa, R., Kanali, C., & Ambassah, N. (2019). Environmental and cost advantages of using polyethylene terephthalate fibre reinforced concrete with fly ash as a partial cement replacement. *Open Journal of Civil Engineering, 9*(4), 281–290. https://doi.org/10.4236/ojce.2019.94020

Ketkukah, T. S., Anowai, S. I., & Mije, F. G. (2022). Performance of olive seed ash as partial replacement of cement in concrete. *Nigerian Journal of Technology, 41*(5), 827–833. https://doi.org/10.4314/njt.v41i5.2

Kumara, G. D., Sivapullaiah, P. V., & Murthy, A. S. N. (2023). Performance evaluation of sugar cane bagasse ash on the strength of concrete: A sustainable approach. *Materials Today: Proceedings, 75*, 106–111. https://doi.org/10.1016/j.matpr.2022.11.335

Ma, X., Zhang, F., & Sun, J. (2022). Flexural performance and thermomechanical coupling analysis of full-iron tailings reinforced concrete beams. *International Journal of Heat and Technology, 40*(3), 806–814. https://doi.org/10.18280/ijht.400320

Nadir, H., Ahmed, A., & West, J. L. (2022). Experimental investigation of engineering properties of iron-based binary and ternary pozzolanic supplementary cementitious materials. *Journal of Materials and Polymer Science*. https://doi.org/10.47485/2832-9384.1024

Neamat, S., & Hassan, M. M. (2021). A review on using ANOVA and RSM modelling in the glass powder replacement of the concrete ingredients. *Journal of Applied Science and Technology Trends, 2*(2), 93–98. https://doi.org/10.38094/jastt202103

Nguyen, T. S. (2020). A study on eco-concrete incorporating fly ash and blast furnace slag in construction in Vietnam. *Applied Mechanics and Materials, 897*, 98–105. https://doi.org/10.4028/www.scientific.net/amm.897.98

Nodehi, M., & Taghvaee, V. M. (2022). Applying circular economy to construction industry through use of waste materials: A review of supplementary cementitious materials, plastics, and ceramics. *Circular Economy and Sustainability, 2*(3), 987–1020. https://doi.org/10.1007/s43615-022-00149-x

Prabagar, S., Thuraisingam, S., & Prabagar, J. (2022). The influence of eco-friendly ash on sustainable construction material: A review. *Applied Science and Innovative Research, 6*(3), 39. https://doi.org/10.22158/asir.v6n3p39

Ramirez, A. M., Manzano, M. A. R., & De Belie, N. (2023). LCA-based recommendations for the selection of eco-concretes using blast furnace slag and fly ash. *MATEC Web of Conferences, 378*, Article 06001. https://doi.org/10.1051/matecconf/202337806001

Tripathi, A., & Mishra, A. (2024). Repairing of concrete structures using nano-silica concrete. *IOP Conference Series: Earth and Environmental Science, 1326*(1), Article 012069. https://doi.org/10.1088/1755-1315/1326/1/012069

Ulucan, M., Gunduzalp, E., Yıldırım, G., Alataş, B., & Alyamaç, K. E. (2024). Optimizing sustainable concrete compressive strength prediction: A new particle swarm optimization-based metaheuristic approach to neural network modeling for circular economy and disaster resilience. *Structural Concrete, 26*(2), 1226–1244. https://doi.org/10.1002/suco.202400070

Wang, R., Qin, R., Li, Y., Li, J., & Zhang, C. (2019). Damage behaviours of concrete and prediction models under the joint effect of freeze–thaw attack and ultraviolet radiation. *Materiales de Construcción, 69*(335), Article e198. https://doi.org/10.3989/mc.2019.12018

Wang, X. H., Tu, J.-T., & Val, D. V. (2024). Influence of supplementary cementitious material on CO_2 balance of cracked RC members in their whole life cycle. *Preprint*. https://doi.org/10.21203/rs.3.rs-3836618/v1

Widjajakusuma, J., Bali, I., Ng, G. P., & Wibowo, K. A. (2022). An experimental study on the mechanical properties of low-aluminum and rich-iron-calcium fly ash-based geopolymer concrete. *Advances in Technology Innovation, 7*(4), 295–302. https://doi.org/10.46604/aiti.2022.10525

Yang, L., Hao, W., He, W., Meng, X., Shen, Y., Du, T., & Wang, H. (2022). Influence of dolomite rock powder and iron tailings powder on the electrical resistivity, strength, and microstructure of cement pastes and concrete. *Coatings, 12*(1), Article 95. https://doi.org/10.3390/coatings12010095

Zhang, Y., Dong, M., Zhang, W., Chen, H., & Yang, D. (2022). Preparation of mineral admixture from iron tailings with steel slag-desulfurization ash and its application to concrete. *Materials, 15*(15), Article 5162. https://doi.org/10.3390/ma15155162

https://doi.org/10.24191/mij.v7i1.11948