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Experimental Investigation On Mechanical Performance Of Steel Fibre Reinforced Fly Ash Concrete

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Abstract
The growing demand for sustainable and high-performance concrete has encouraged the combined use of supplementary cementitious materials and fibre reinforcement to enhance mechanical behavior while reducing environmental impact. In this study, the fresh and hardened properties of M20 and M30 grade concretes incorporating fly ash as a partial replacement of cement and steel fibres as discrete reinforcement were experimentally investigated. Fly ash was used in the range of 0–35%, while steel fibre content was varied from 0 to 2.0% by volume of concrete. The workability of fresh concrete was evaluated using the slump test in accordance with IS 1199 (Part 4):2018. The hardened mechanical performance was assessed through compressive strength, split tensile strength, and flexural strength tests conducted at 7 and 28 days of curing as per IS 516:1959. The results indicate that increasing fly ash content leads to a marginal reduction in early-age strength and workability due to delayed pozzolanic activity, with a more pronounced effect on tensile-related properties than on compressive strength. However, the incorporation of steel fibres significantly enhanced split tensile and flexural strength by improving crack resistance, stress redistribution, and post-cracking behavior. Compressive strength showed only moderate improvement with fibre addition, whereas substantial gains were observed in tensile and bending performance. For both M20 and M30 grades, mixes containing 1.5–2.0% steel fibres combined with 15–20% fly ash replacement exhibited the most balanced mechanical performance at 28 days. Higher fly ash contents resulted in strength reduction despite fibre addition due to cement dilution effects. the study demonstrates that the synergistic use of steel fibres and fly ash can produce concrete with enhanced tensile and flexural performance and improved sustainability, making it suitable for structural applications governed by bending and tensile stresses such as pavements, slabs, and beams.
Keywords: Steel fibre reinforced concrete; Fly ash; Compressive strength; Split tensile strength; Flexural strength

INTRODUCTION

Concrete remains the most widely used construction material due to its versatility, durability, and economic feasibility. However, the increasing demand for sustainable construction materials and enhanced structural performance has driven extensive research into the incorporation of supplementary cementitious materials and fibre reinforcement. Among these, fly ash has gained significant attention as a partial replacement for cement owing to its ability to improve long-term strength development, reduce heat of hydration, and minimize environmental impact. Nevertheless, fly ash replacement is often associated with reduced early-age strength and limited tensile performance, particularly in conventional concrete mixes.

Steel fibre reinforcement has emerged as an effective approach to overcome the inherent brittleness and low tensile capacity of concrete. The inclusion of discrete steel fibres improves crack resistance, energy absorption, and post-cracking behaviour by bridging microcracks and delaying crack propagation. While steel fibres contribute modestly to compressive strength, their influence is particularly pronounced in split tensile and flexural performance, which govern the structural response of concrete elements subjected to tensile stresses and bending actions. The combined use of steel fibres and fly ash therefore offers a promising strategy to develop concrete with improved mechanical performance and enhanced sustainability.

Despite the advantages, the simultaneous incorporation of fly ash and steel fibres alters the fresh and hardened properties of concrete, necessitating systematic experimental evaluation. Workability is a critical fresh concrete property, as excessive fibre content and fine fly ash particles can adversely affect consistency and ease of placement. Similarly, the hardened mechanical properties, including compressive, split tensile, and flexural strength, must be evaluated to understand the structural implications of these modifications.

In the present study, the fresh and hardened properties of M20 and M30 grade concretes incorporating varying proportions of steel fibres (0–2.0%) and fly ash replacement (0–35%) were experimentally investigated. The workability of fresh concrete was assessed using the slump test in accordance with IS 1199 (Part 4):2018 to evaluate the consistency and flow characteristics of the mixes. The hardened mechanical performance was examined through standardized compressive strength, split tensile strength, and flexural strength tests conducted as per IS 516:1959. Compressive strength tests were performed on cube specimens using a hydraulic compression testing machine to determine load-carrying capacity under axial compression. Split tensile strength was evaluated using cylindrical specimens subjected to diametral compression to assess tensile resistance and crack development. Flexural strength was determined on prism specimens under two-point loading to evaluate bending resistance and post-cracking behaviour. By integrating the effects of fly ash replacement and steel fibre reinforcement, this study aims to identify optimal combinations that enhance tensile and flexural performance without compromising compressive strength and workability. The findings provide valuable insights into the suitability of fibre-reinforced fly ash concrete for structural applications such as pavements, slabs, beams, and other elements predominantly subjected to tensile and bending stresses, while also contributing to sustainable construction practices.

LITERATURE REVIEW

The last two decades have seen substantial progress in developing sustainable, higher-performance concretes by combining supplementary cementitious materials with discrete fibre reinforcement. Fly ash has been widely adopted as a partial cement replacement to reduce embodied carbon and improve long-term durability; however, its slower pozzolanic reaction often reduces early-age strength and affects tensile-related properties (Mehta, 2001; Thomas, 2007). Steel fibres have been repeatedly shown to enhance cracking resistance, toughness and post-crack behaviour, with disproportionate benefits for tensile and flexural performance compared with compressive strength (Song & Hwang, 2004; Yazıcı et al., 2007). Recent meta-analyses and scientometric reviews confirm that steel fibre volume fraction, aspect ratio and matrix quality are primary determinants of mechanical gains (Amin, 2022). Studies combining fly ash and steel fibres indicate a synergistic potential when fly ash replacement is limited to moderate levels. Experimental investigations report that 15–20% fly ash with 0.5–2.0% steel fibres often yields an optimal balance between sustainability and mechanical performance—mitigating early-age losses while achieving marked improvements in splitting tensile and flexural strengths at 28 days (Ali et al., 2021). Mechanistically, fibres compensate for delayed matrix strength by bridging microcracks and enhancing stress transfer across the interfacial transition zone (ITZ), thereby improving toughness and serviceability even when compressive strength gains remain modest (Afroughsabet & Ozbakkaloglu, 2015). Matrix strength itself amplifies fibre efficiency; higher-grade concretes (e.g., M30) typically display greater fibre effectiveness due to denser packing and stronger fibre–matrix bonds (Xu et al., 2020).
Recent 2020–2025 investigations have expanded the scope to include shrinkage behavior, workability tradeoffs, hybrid fibres and geopolymer binders, highlighting that fibre content and mix design must be optimized together to avoid severe loss of fresh-state workability or diminished long-term durability (Pham, 2025; Abedi, 2025). The body of evidence thus supports targeted use of fly ash (≈15–20%) with steel fibre dosages up to ~2% by volume to achieve sustainable mixes with superior tensile and flexural performance suitable for pavements, slabs and other bending-critical elements.

MATERIALS AND METHODS

Ordinary Portland Cement conforming to relevant Indian Standards was used as the primary binder, with fly ash employed as a supplementary cementitious material at replacement levels ranging from 0 to 35% by weight of cement. Natural river sand and crushed coarse aggregate with a nominal maximum size of 20 mm were used as fine and coarse aggregates, respectively, both satisfying the grading and quality requirements of Indian Standards. Potable water free from harmful impurities was used for mixing and curing. Hooked-end steel fibres were incorporated as discrete reinforcement in proportions of 0, 0.5, 1.0, 1.5, and 2.0% by volume of concrete. Two grades of concrete, M20 and M30, were designed using the Indian Standard mix design approach. For each grade, a control mix without fly ash and steel fibres was prepared, followed by mixes incorporating different combinations of fly ash replacement and steel fibre content. Concrete mixing was carried out by initially dry-mixing cement, fly ash, and aggregates to ensure

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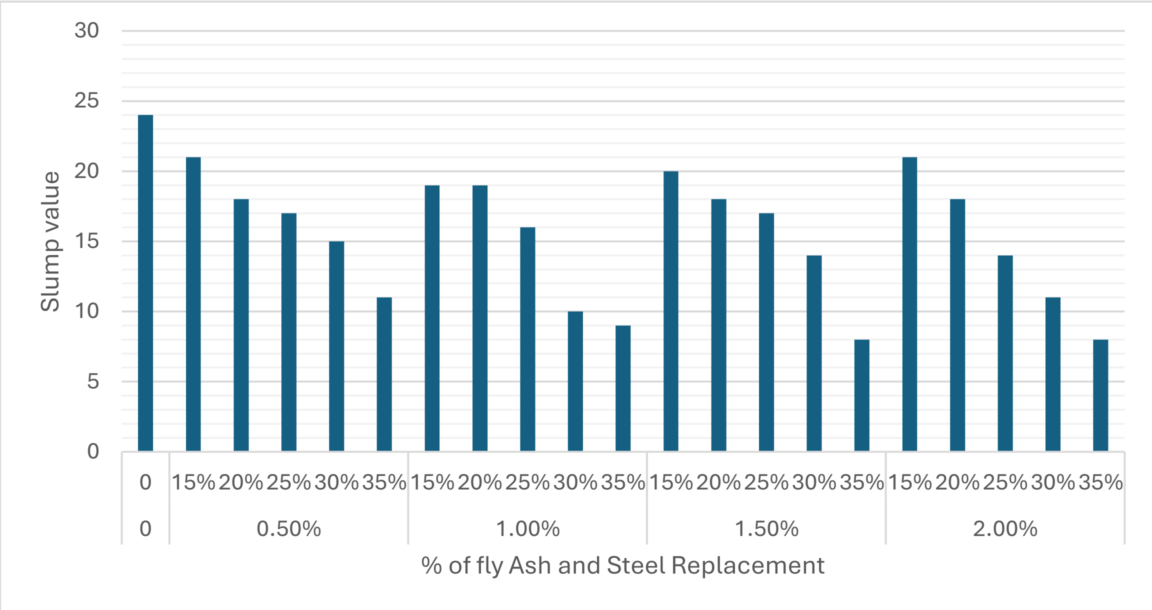
uniformity, after which steel fibres were gradually introduced to achieve proper dispersion, followed by the addition of water.

The workability of fresh concrete was evaluated immediately after mixing using the slump test in accordance with IS 1199 (Part 4):2018. For hardened concrete properties, cube specimens were cast for compressive strength testing, cylindrical specimens for split tensile strength testing, and prism specimens for flexural strength testing. All specimens were compacted, demoulded after 24 hours, and cured in water until the age of testing. Compressive, split tensile, and flexural strength tests were conducted at 7 and 28 days of curing in accordance with IS 516:1959. For each test and mix combination, multiple specimens were tested and the average values were reported. The experimental results were analyzed to assess the individual and combined effects of fly ash replacement and steel fibre incorporation on the fresh and hardened mechanical properties of M20 and M30 grade concretes.

Workability Characteristics – Slump Test Results (Slump Behaviour of M20 Grade Concrete)

The variation of slump values for M20 grade concrete incorporating different percentages of steel fibre and fly ash replacement is graphically illustrated in Figure 1. The control mix (0% steel fibre and 0% fly ash) exhibited a slump value of 24 mm, indicating low to medium workability, which is typical for fibre-free conventional concrete.

Figure 1: Variation of Slump Value for M20 Grade Concrete with Different Percentages of Steel Fibre



and Fly Ash Replacement

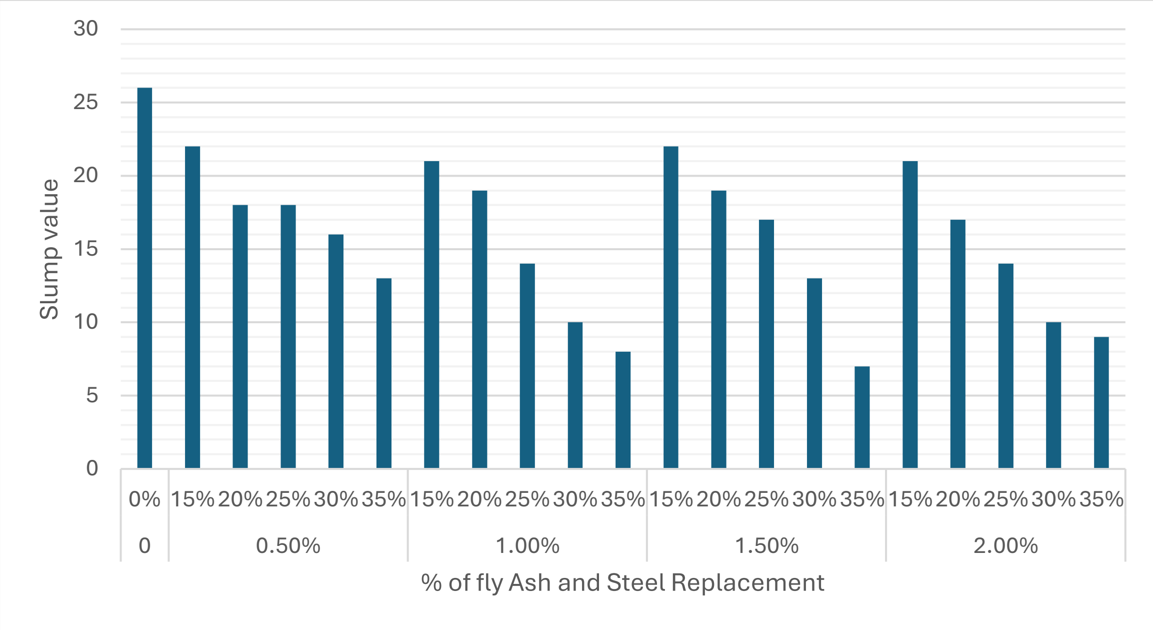
With the introduction of steel fibres and fly ash, a progressive reduction in slump was observed across all mix combinations. At 0.50% steel fibre replacement, the slump decreased from 21 mm at 15% fly ash to 11 mm at 35% fly ash, demonstrating the combined influence of fibre addition and increased fly ash content on workability. This reduction can be attributed to the higher surface area and angularity of steel fibres, which restrict the free flow of the cementitious matrix, along with the fineness and increased water demand of fly ash.

A similar trend was observed at higher steel fibre contents of 1.00%, 1.50%, and 2.00%, where the slump values consistently declined with increasing fly ash replacement. Notably, at 1.00% steel fibre and 35% fly ash, the slump reduced sharply to 9 mm, while at 2.00% steel fibre and 35% fly ash, the minimum slump value of 8 mm was recorded. These results indicate a significant loss of workability at higher fibre dosages, primarily due to fibre interlocking and reduced paste mobility. The results depicted in Figure 1 clearly demonstrate that although moderate fly ash replacement (15–20%) maintains acceptable workability levels, higher fly ash contents combined with steel fibre percentages beyond 1.0% lead to pronounced reductions in slump, necessitating the use of chemical admixtures for practical applications.

Slump Behaviour of M30 Grade Concrete

The slump characteristics of M30 grade concrete mixes containing steel fibre and fly ash replacement are illustrated in Figure 2. The control M30 mix exhibited a slump value of 26 mm, which is marginally higher than that of the M20 control mix, reflecting the improved paste quality and higher cementitious content typically associated with higher-grade concrete.

Figure 2: Variation of Slump Value for M30 Grade Concrete with Different Percentages of Steel Fibre



and Fly Ash Replacement

At 0.50% steel fibre content, the slump values decreased from 22 mm at 15% fly ash to 13 mm at 35% fly ash, indicating a trend similar to that observed for M20 grade concrete. However, for equivalent replacement levels, the M30 mixes consistently recorded slightly higher slump values, suggesting better workability retention due to enhanced paste volume and improved particle packing. With an increase in steel fibre content to 1.00% and 1.50%, a notable reduction in slump was evident, particularly beyond 25% fly ash replacement. The lowest slump value of 7 mm was observed at 1.50% steel fibre and 35% fly ash, indicating very stiff concrete. At 2.00% steel fibre replacement, the slump values ranged from 21 mm at 15% fly ash to 9 mm at 35% fly ash, confirming the adverse effect of higher fibre dosages on fresh concrete workability.

The graphical representation in Figure 2 highlights that, despite the overall decline in slump with increasing steel fibre and fly ash content, M30 grade concrete demonstrates comparatively better workability than M20 grade concrete at similar replacement levels. This behavior can be attributed to the higher cement content and improved cohesiveness of the M30 mix.

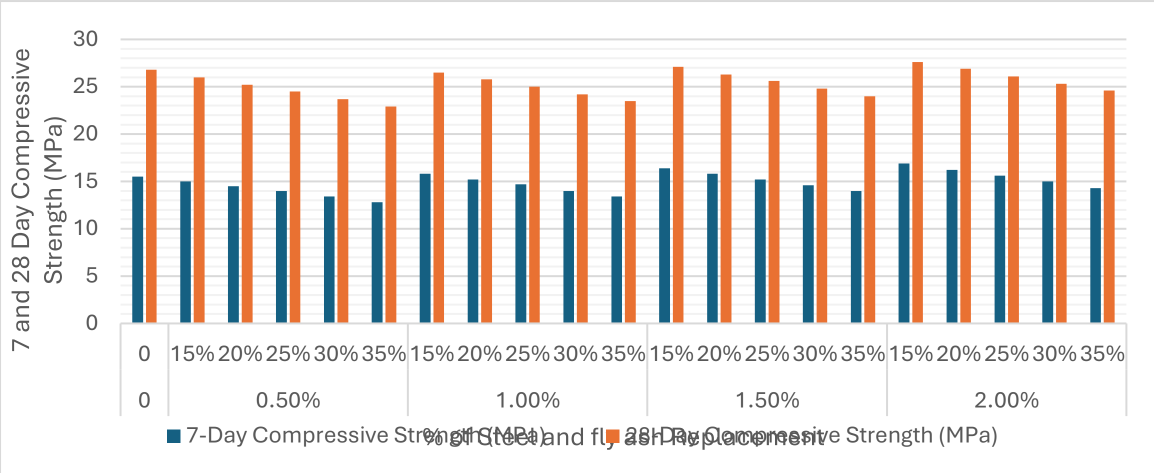
Comparative Observations

A comparative analysis of Figures 1 and 2 reveals that both M20 and M30 grade concretes exhibit a systematic reduction in slump with increasing steel fibre and fly ash replacement. However, the reduction is more pronounced in M20 grade concrete, whereas M30 grade concrete maintains marginally higher slump values due to its richer mix composition. These findings emphasize that while steel fibres enhance mechanical performance, their dosage must be carefully optimized to balance workability, particularly when combined with higher fly ash replacement levels.

7-Day and 28-Day Compressive Strength of M20 Grade Concrete

The variation in 7-day and 28-day compressive strength of M20 grade concrete incorporating different percentages of steel fibre and fly ash replacement is illustrated in Figure 3. The control mix (0% steel fibre and 0% fly ash) attained compressive strengths of 15.5 MPa at 7 days and 26.8 MPa at 28 days, confirming the adequacy of the base mix design.

Figure 3: Variation of 7-Day and 28-Day Compressive Strength of M20 Grade Concrete with Different Percentages of Steel Fibre and Fly Ash Replacement



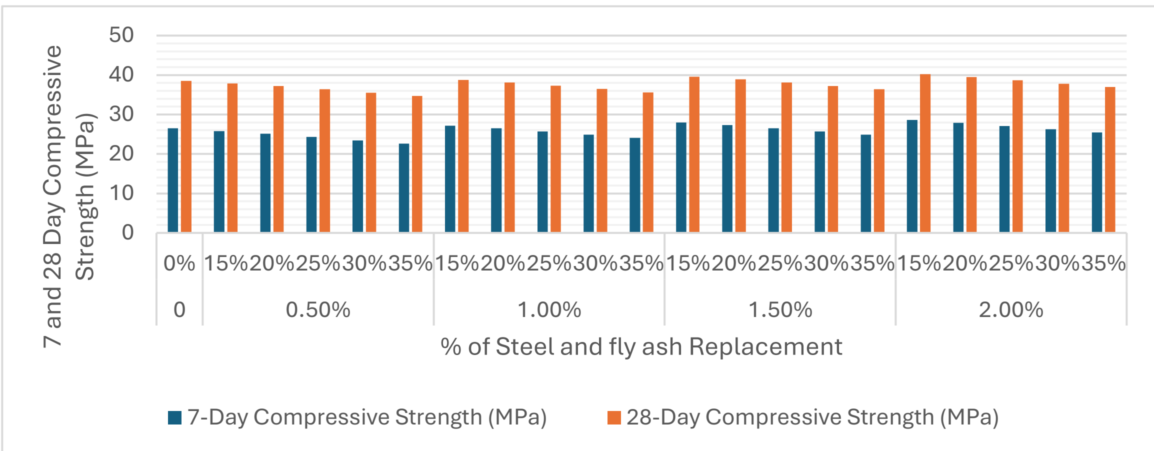
As observed in Figure 3, the inclusion of fly ash at lower replacement levels (15–20%) resulted in marginal reductions in early-age strength, particularly at 7 days, which can be attributed to the slower pozzolanic reaction of fly ash compared to ordinary Portland cement. However, the incorporation of steel fibres significantly compensated for this reduction. At 1.50% and 2.00% steel fibre contents, the 28-day compressive strength exceeded that of the control mix for fly ash contents up to 20%, indicating improved stress transfer and crack-bridging action provided by the fibres.

With further increase in fly ash replacement beyond 25–30%, a gradual decline in both 7-day and 28-day strengths was evident across all fibre contents. The reduction is more pronounced at early ages, whereas the 28-day strength remained relatively stable, particularly for mixes containing 1.5–2.0% steel fibres, as shown in Figure 4.3. The highest 28-day compressive strength of 27.6 MPa was recorded for the mix containing 2.0% steel fibre and 15% fly ash, demonstrating an optimal balance between fibre reinforcement and supplementary cementitious material content. Figure 3 indicates that steel fibre addition enhances the compressive strength development of M20 concrete, particularly at later ages, while excessive fly ash replacement adversely affects strength due to dilution of cementitious compounds.

7-Day and 28-Day Compressive Strength of M30 Grade Concrete

The compressive strength development of M30 grade concrete with varying steel fibre and fly ash replacement levels is presented graphically in Figure 4, The control M30 mix achieved compressive strengths of 26.5 MPa at 7 days and 38.5 MPa at 28 days, reflecting the higher cementitious content and improved matrix densification associated with higher-grade concrete. Figure 4.4 demonstrates that M30 concrete exhibited a more pronounced strength gain compared to M20, particularly at higher steel fibre contents. At 1.0–2.0% steel fibre replacement, the 28-day compressive strength consistently surpassed that of the control mix for fly ash contents up to 20%, indicating enhanced confinement and effective crack arresting mechanisms. The maximum 28-day strength of 40.2 MPa was observed at 2.0% steel fibre and 15% fly ash, representing an increase of approximately 4.4% over the control mix.

Figure 3: Variation of 7-Day and 28-Day Compressive Strength of M30 Grade Concrete with Different Percentages of Steel Fibre and Fly Ash Replacement



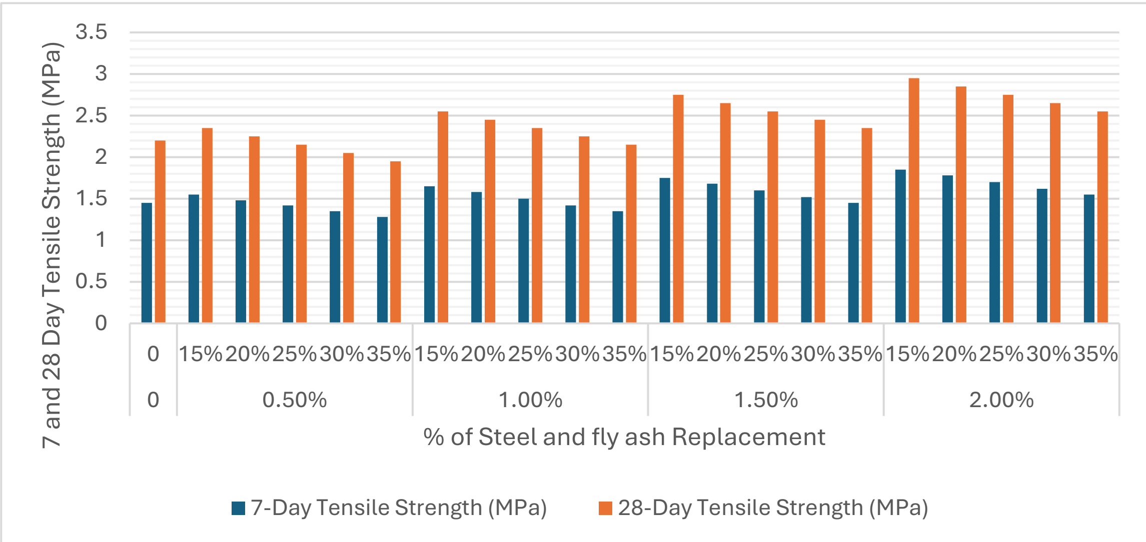
M20 concrete, an increase in fly ash replacement beyond 25–30% led to a gradual reduction in compressive strength at both curing ages. Nevertheless, the strength reduction in M30 concrete was comparatively less severe, as evident from Figure 4, owing to the higher binder content and improved particle packing density, which mitigated the dilution effect of fly ash. The comparative trend observed in Figure 4 confirms that steel fibre incorporation is more effective in higher-grade concrete, enabling improved utilization of fly ash without significant loss of strength. This synergistic behavior highlights the suitability of fibre-reinforced fly ash concrete for structural applications requiring enhanced mechanical performance.

Split Tensile Strength Characteristics of M20 Grade Concrete

The variation in 7-day and 28-day split tensile strength of M20 grade concrete incorporating steel fibres and fly ash replacement is illustrated in Figure 5. The control mix without steel fibres and fly ash exhibited a 28-day split tensile strength of 2.20 MPa, which is representative of the tensile performance of conventional M20 grade concrete.

As observed in Figure 5, the 7-day split tensile strength shows a gradual reduction with increasing fly ash replacement for all steel fibre contents. This trend is primarily attributed to the slower pozzolanic activity of fly ash, which delays early-age bond development within the cementitious matrix and consequently reduces tensile resistance during the initial curing period. Despite this reduction, mixes incorporating steel fibres consistently demonstrated higher early-age tensile strength than the control mix, indicating the beneficial role of fibres in limiting microcrack initiation and enhancing stress transfer.

Figure 5: Variation of 7-Day and 28-Day Split Tensile Strength of M20 Grade Concrete with Different Percentages of Steel Fibre and Fly Ash Replacement



At 28 days, a clear enhancement in split tensile strength was observed with increasing steel fibre content. Mixes containing 1.5–2.0% steel fibres combined with 15–20% fly ash replacement exhibited the highest tensile strength values. The maximum 28-day split tensile strength of 2.95 MPa was achieved for the mix containing 2.0% steel fibres and 15% fly ash, corresponding to an improvement of approximately 34% compared to the control mix. This enhancement is attributed to effective fibre bridging across microcracks, improved stress redistribution, and delayed crack propagation under tensile loading.

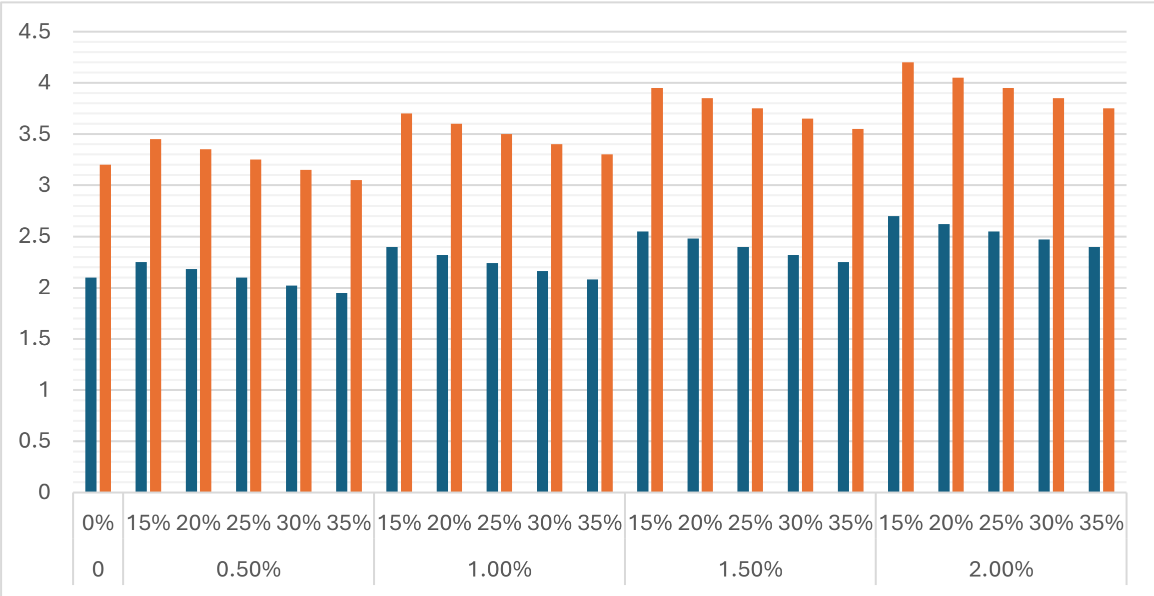
At higher fly ash replacement levels of 25–35%, a gradual reduction in split tensile strength was observed despite fibre addition. This reduction is associated with the dilution of cementitious phases and delayed development of a dense interfacial transition zone. Nevertheless, fibre-reinforced mixes consistently outperformed the plain concrete mix at comparable fly ash levels, demonstrating that steel fibres play a dominant role in improving the tensile performance of M20 grade concrete, while fly ash replacement should be optimized within 15–20% to balance mechanical performance and sustainability.

Split Tensile Strength Characteristics of M30 Grade Concrete

The split tensile strength characteristics of M30 grade concrete incorporating steel fibres and fly ash replacement at 7 and 28 days are presented in Figure 4.6. The control mix exhibited a 28-day split tensile strength of 3.20 MPa, reflecting the enhanced tensile capacity associated with higher-grade concrete and increased binder content.

As shown in Figure 6, the 7-day split tensile strength exhibited a progressive reduction with increasing fly ash replacement across all fibre dosages. This behavior is attributed to the delayed pozzolanic reaction of fly ash, which restricts early-age strength development. However, even at early curing stages, the inclusion of steel fibres resulted in a noticeable improvement in tensile strength compared to the control mix, confirming their effectiveness in restricting microcrack formation and enhancing load transfer within the matrix.

Figure 6: Variation of 7-Day and 28-Day Split Tensile Strength of M30 Grade Concrete with Different Percentages of Steel Fibre and Fly Ash Replacement



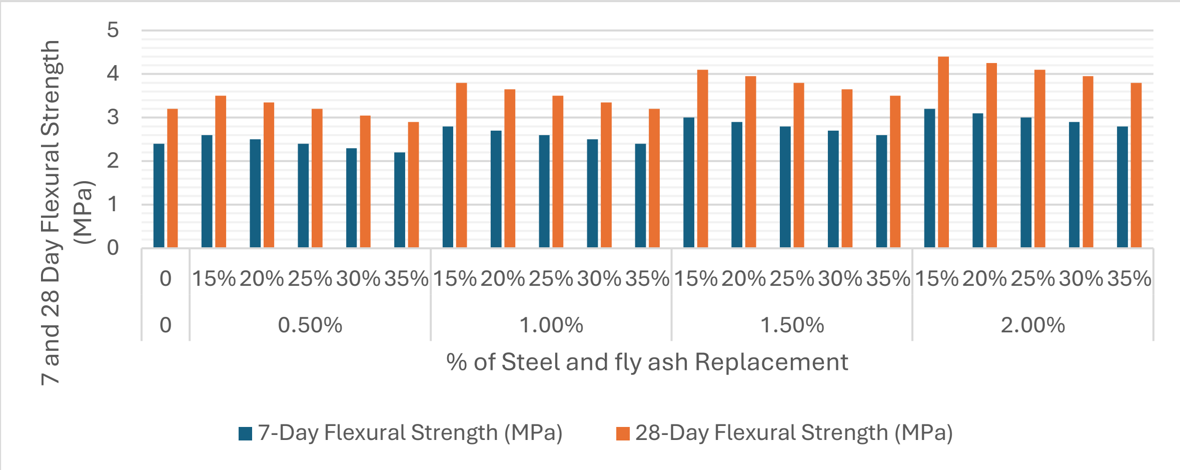
At 28 days, M30 grade concrete demonstrated a more pronounced improvement in split tensile strength compared to M20 grade concrete. Mixes containing 1.5–2.0% steel fibres with 15–20% fly ash replacement achieved the highest tensile strength values. The maximum 28-day split tensile strength of 4.20 MPa was recorded for the mix containing 2.0% steel fibres and 15% fly ash, representing an increase of approximately 31% over the control mix. This superior performance is attributed to a stronger fibre–matrix bond, denser microstructure, and improved interfacial transition zone characteristics in higher-grade concrete.

At higher fly ash replacement levels of 25–35%, a gradual reduction in tensile strength was observed despite fibre addition, owing to the dilution of cementitious phases and delayed matrix densification. Nevertheless, all fibre-reinforced mixes consistently exhibited higher tensile strength than the plain concrete mix, highlighting the effectiveness of steel fibres in enhancing tensile resistance. Overall, Figure 6 indicates that steel fibre reinforcement has a more pronounced influence on the tensile performance of M30 grade concrete than M20 grade concrete, while fly ash replacement should be limited to 15–20% to achieve an optimal balance between tensile strength enhancement and sustainable material utilization.

Flexural Strength Characteristics of M20 Grade Concrete

The variation in 7-day and 28-day flexural strength of M20 grade concrete incorporating different percentages of steel fibres and fly ash replacement is illustrated in Figure 7. The control mix without steel fibres and fly ash exhibited a 28-day flexural strength of 3.2 MPa, which is characteristic of conventional M20 grade concrete and reflects its limited tensile resistance under bending.

Figure 7: Variation of 7-Day and 28-Day Flexural Strength of M20 Grade Concrete with Different Percentages of Steel Fibre and Fly Ash Replacement



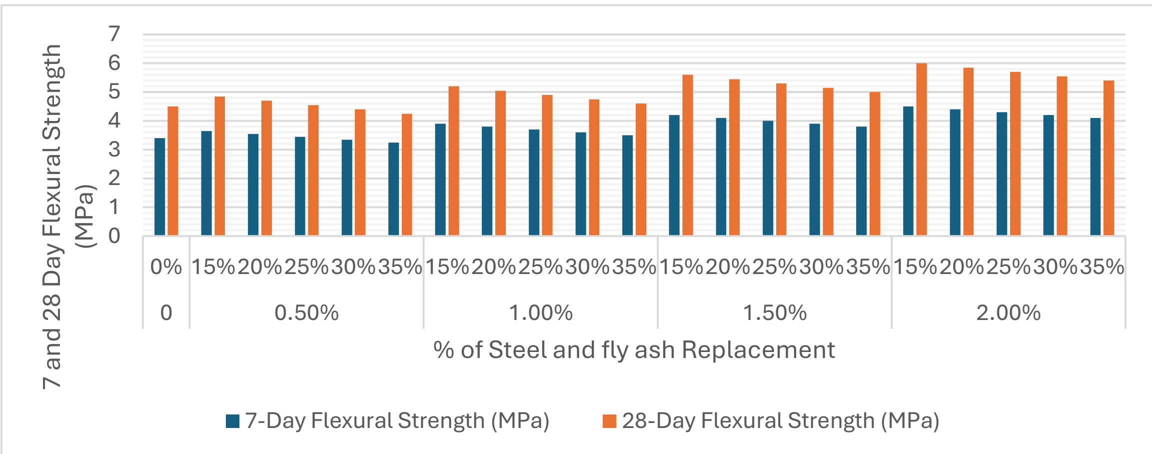
As observed in Figure 7, the 7-day flexural strength showed a gradual reduction with increasing fly ash replacement across all steel fibre contents. This behavior is attributed to the delayed pozzolanic reaction of fly ash, which restricts early-age bond development within the cementitious matrix and reduces stiffness under flexural loading. Despite this reduction, mixes incorporating steel fibres consistently demonstrated higher early-age flexural strength than the control mix, indicating the effectiveness of fibres in bridging microcracks and limiting crack initiation even at early curing stages.

At 28 days, a substantial enhancement in flexural strength was observed with increasing steel fibre content. Mixes containing 1.5–2.0% steel fibres combined with 15–20% fly ash replacement exhibited the highest flexural strength values. The maximum 28-day flexural strength of 4.4 MPa was recorded for the mix containing 2.0% steel fibres and 15% fly ash. This improvement is attributed to effective fibre bridging, enhanced stress redistribution, and increased post-cracking load-carrying capacity under bending. The gain in flexural strength was notably higher than the corresponding increase in compressive strength, highlighting the dominant role of steel fibres in improving bending resistance.

At higher fly ash replacement levels of 25–35%, a gradual decline in flexural strength was observed despite fibre addition. This reduction is primarily associated with dilution of cementitious material and slower strength development, which weakens the fibre–matrix bond. Nevertheless, all fibre-reinforced mixes consistently exhibited superior flexural performance compared to the plain concrete mix at similar fly ash contents. The results shown in Figure 4.7 indicate that steel fibre incorporation significantly enhances the flexural strength of M20 grade concrete, while fly ash replacement should be optimized within 15–20% to achieve a balance between flexural performance and sustainable material utilization.

Flexural Strength Characteristics of M30 Grade Concrete

The flexural strength development of M30 grade concrete incorporating steel fibres and fly ash replacement at 7 and 28 days of curing is illustrated in Figure 8. The control mix exhibited a 28-day flexural strength of 4.5 MPa, reflecting the higher tensile resistance and improved matrix quality associated with higher-grade concrete compared to M20.Figure 8: Variation of 7-Day and 28-Day Flexural Strength of M30 Grade Concrete with Different Percentages of Steel Fibre and Fly Ash Replacement



As shown in Figure 4.8, a marginal reduction in 7-day flexural strength was observed with increasing fly ash replacement for all fibre dosages. This trend is linked to the delayed pozzolanic reaction of fly ash, which limits early-age stiffness and bond development. However, the presence of steel fibres significantly enhanced early-age flexural strength relative to the control mix, confirming their role in restricting microcrack formation and improving stress transfer under bending loads.
At 28 days, M30 grade concrete exhibited a pronounced improvement in flexural strength with increasing steel fibre content. Mixes containing 1.5–2.0% steel fibres combined with 15–20% fly ash replacement achieved the highest flexural strength values. The maximum 28-day flexural strength of 6.0 MPa was recorded for the mix containing 2.0% steel fibres and 15% fly ash. This superior performance is attributed to effective fibre bridging, enhanced post-cracking resistance, and a stronger fibre–matrix bond resulting from the denser microstructure of M30 grade concrete. The improvement in flexural strength was more pronounced than the corresponding increase in compressive strength, emphasizing the dominant contribution of steel fibres to bending performance.
At higher fly ash replacement levels of 25–35%, a gradual decrease in flexural strength was observed despite fibre incorporation. This reduction is primarily due to dilution of cementitious phases and reduced fibre–matrix bond strength caused by slower strength development. Nevertheless, all fibre-reinforced mixes demonstrated superior flexural performance compared to the control mix at comparable fly ash contents. Overall, Figure 8 indicates that steel fibre reinforcement is particularly effective in enhancing the flexural performance of M30 grade concrete, while fly ash replacement should be maintained within 15–20% to achieve an optimal balance between flexural strength enhancement and sustainability.

SUMMARY AND CONCLUSIONS

The combined behaviour of compressive, split tensile, and flexural strength for M20 and M30 grade concretes incorporating steel fibres and fly ash replacement demonstrates a consistent and interrelated performance trend, as illustrated in Figures 3–8. Across both grades, the mechanical response is governed by the competing influences of fibre reinforcement and partial cement replacement with fly ash.
At early ages, both compressive and tensile-related properties (split tensile and flexural strength) exhibited a reduction with increasing fly ash replacement. This trend is particularly evident in the 7-day results and is attributed to the slower pozzolanic reaction of fly ash, which delays strength development and reduces early-age matrix stiffness. The reduction is more pronounced in split tensile and flexural strength than in compressive strength, indicating that tensile-dominated properties are more sensitive to early-age microstructural deficiencies and bond development.
With increasing curing age, a clear divergence in strength behaviour was observed. While compressive strength showed moderate improvement with steel fibre addition, the enhancement in split tensile and flexural strength was significantly higher. This indicates that steel fibres play a secondary role in compressive load resistance but exert a dominant influence on tensile and bending performance. The improvement in tensile-related properties is primarily attributed to effective fibre bridging across microcracks, delayed crack initiation, and enhanced stress redistribution within the cementitious matrix.
For both M20 and M30 grade concretes, mixes containing 1.5–2.0% steel fibres combined with 15–20% fly ash replacement consistently exhibited the best overall mechanical performance at 28 days, as evident from Figures 3–8. In this range, compressive strength was either comparable to or higher than the control mix, while split tensile and flexural strengths showed substantial improvements. Beyond 25–30% fly ash replacement, all strength parameters showed a gradual decline despite fibre addition, indicating a dominant dilution effect of cementitious phases and delayed formation of a dense interfacial transition zone.
A comparative assessment between M20 and M30 grade concretes reveals that the beneficial effects of steel fibre incorporation are more pronounced in M30 grade concrete. The higher binder content and denser matrix of M30 concrete promote stronger fibre–matrix bonding and more efficient stress transfer, resulting in greater improvements in split tensile and flexural strength relative to compressive strength. In contrast, M20 concrete exhibited similar trends but with relatively lower magnitude of strength enhancement, highlighting the influence of matrix quality on fibre efficiency.
Overall, the integrated results confirm that compressive strength alone is insufficient to capture the performance benefits of steel fibre reinforcement. While fly ash replacement influences early-age strength development, its optimal utilization in combination with steel fibres (15–20%) enables sustainable

concrete production without compromising mechanical performance. The pronounced improvement in split tensile and flexural strength relative to compressive strength underscores the suitability of fibre-reinforced fly ash concrete for structural applications governed by tensile stresses and bending actions, such as pavements, slabs, beams, and industrial flooring.

CONCLUSION

This study investigated the combined influence of steel fibre incorporation and fly ash replacement on the compressive, split tensile, and flexural strength characteristics of M20 and M30 grade concretes. Based on the experimental results and integrated discussion, the following conclusions are drawn.

The incorporation of fly ash resulted in a marginal reduction in early-age strength for both grades of concrete due to delayed pozzolanic activity. This effect was more pronounced in tensile-related properties than in compressive strength, indicating the greater sensitivity of split tensile and flexural behaviour to early-age matrix development. However, at later curing ages, fly ash contributed to improved matrix densification when used within optimal limits.

Steel fibre addition significantly enhanced the mechanical performance of concrete, particularly the split tensile and flexural strengths. While compressive strength exhibited only moderate improvement with fibre inclusion, substantial gains were observed in tensile and bending resistance due to effective fibre bridging, delayed crack initiation, and improved stress redistribution. This confirms that the primary contribution of steel fibres lies in improving post-cracking behaviour rather than compressive load resistance.

For both M20 and M30 grade concretes, mixes containing 1.5–2.0% steel fibres with 15–20% fly ash replacement demonstrated the most balanced and superior performance at 28 days. Within this range, compressive strength was maintained at or above the control mix level, while split tensile and flexural strengths showed significant enhancement. Fly ash replacement beyond 25–30% led to a gradual decline in all strength parameters despite fibre addition, highlighting the dominance of cement dilution and delayed interfacial transition zone development at higher replacement levels.

A comparative evaluation revealed that M30 grade concrete exhibited greater improvements in tensile and flexural strength than M20 grade concrete for similar fibre dosages, owing to its higher binder content and denser microstructure, which facilitated stronger fibre–matrix bonding. This underscores the importance of matrix quality in maximizing the effectiveness of steel fibre reinforcement. The findings demonstrate that the synergistic use of steel fibres and fly ash can produce concrete with improved mechanical performance and enhanced sustainability when properly optimized. The pronounced improvement in tensile and flexural strength relative to compressive strength highlights the suitability of fibre-reinforced fly ash concrete for structural applications governed by bending and tensile stresses, such as pavements, slabs, beams, and industrial flooring.

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