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Experimental Investigation On Siesmic Behaviour Of Self Compacting Concrete With Steel Fibers

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Abstract
Self-Compacting Concrete (SCC) is an innovative concrete mix that flows without the need for vibration or compaction, using higher cement content, which raises environmental concerns. To address this, industrial byproducts like fly ash, silica fume, and rice husk ash can replace cement, reducing the environmental impact. This study explores the use of these materials in SCC for M30 grade concrete and evaluates the effects of adding corrugated steel fibers to improve strength and crack resistance. Optimal mixes enhance mechanical properties and seismic performance, offering sustainable alternatives to traditional concrete.

Keywords: SFRSCC, SCC, fly ash, silica fume, and rice husk ash.

1. General

Concrete is a brittle composite material made of water and coarse aggregates bound by cement. Its workability depends on its ease of placement and compaction without bleeding or segregation. Self-Compacting Concrete (SCC) is a highly fluid mix that flows under its own weight, making it ideal for densely reinforced structures. It is often called "High Performance Concrete" (HPC), though its definition varies. While steel reinforcement improves concrete strength, fibers are added to control microcracks and improve tensile and flexural strength.

SCC was first developed in 1988 to enhance concrete durability. Okamura et al. (1995) proposed a mix proportioning system for SCC with fixed contents for aggregates, adjusting superplasticizer dosage and water-to-powder ratio to achieve self-compactibility. Research on SCC has been conducted worldwide, leading to various guidelines and recommendations, such as those from Japan and the European Federation of Specialist Construction Chemicals (EFNARC).

SCC reduces construction time and ensures proper compaction in confined areas, eliminating vibration noise. Adding steel fiber reinforcement improves SCC's post-cracking behavior, turning its brittle nature into pseudo-ductility. Steel Fiber Reinforced SCC (SFRSCC) offers technical advantages, especially in earthquake-resistant structures, by enhancing ductility.

SCC lacks a standard mix design, and fiber reinforcement cannot replace traditional steel bars. While fibers control cracks and shrinkage better due to their closer spacing, steel fibers may not offer adequate corrosion resistance in exposed conditions. The absence of a design method to limit crack width is a drawback for using steel fiber reinforcement.

This research investigates the use of mineral admixtures such as fly ash, silica fume, and rice husk ash as replacements for cement in self-compacting concrete (SCC), along with the addition of corrugated steel fibers to enhance its properties. Fly ash improves workability and durability but slows early strength development, while silica fume increases strength by reducing bleeding and enhancing cohesion. Rice husk ash, a sustainable byproduct, offers a high silicon oxide content, making it an effective cement alternative. The study aims to explore the effects of these admixtures on SCC's workability and the seismic performance of reinforced concrete. Corrugated steel fibers, which are cost-effective and easy to mix, provide multi-directional reinforcement, enhancing impact resistance, fatigue endurance, and overall structural performance. By examining the optimal mix of admixtures and fibers, the research seeks to improve the durability, flexibility, and seismic resistance of SCC, making it a more suitable choice for earthquake-resistant structures. Ultimately, the goal is to develop an eco-friendly concrete mix that offers improved strength and reduced environmental impact.

Methodology

The research begins by addressing the fundamental material properties, SCC mix proportioning, and workability of developed SCC mixes, both with and without fibers. In the second phase, essential strength tests are conducted on these mixes, leading to the identification of the optimal SCC mix with the ideal fiber content. The third phase involves investigating the behavior of structural members, such as bars and bar-column joints, under various loading conditions using the optimized mixes. Finally, a comparative analysis between the experimental results and software simulations is conducted, and conclusions are drawn from the findings.

2. Literature Review

Various researchers have explored SCC over the years. Nikbin et al. (2014) found that increasing the water-to-cement (w/c) ratio from 0.35 to 0.7 resulted in a 66% reduction in compressive strength, with the w/c ratio having a more significant impact on compressive strength and split tensile strength than on the modulus of elasticity. Beata (2014) studied the effects of different superplasticizers, discovering that they influence SCC air content differently, although the mixes did not meet EFNARC standards. Wolfram et al. (2014) investigated superplasticizers at temperatures between 5°C and 30°C, finding that highly charged polycarboxylate polymer superplasticizers performed best at low temperatures, while their flow properties decreased at higher temperatures.

Sideris and Anagnostopoulos (2013) emphasized the durability of SCC, noting that it exhibited greater durability than conventional vibrated concrete due to lower carbonation depth and chloride penetration, particularly at higher w/c ratios. Sfikas and Trezos examined SCC's bond behavior and found that SCC generally exhibited superior bond stress and lower bond stress variability compared to conventional vibrated concrete.

Rafat et al. (2012) studied fly ash replacement in cement and found that the optimal replacement rate lies between 25% and 35%. Farhad and Nejadi (2012) proposed a modified stress-strain model that aligned with experimental results. Iliana et al. (2012) investigated moderate-strength SCC and observed changes by increasing the w/fines ratio from 0.38 to 0.42.

As powder content increases in SCC, strength and modulus of elasticity tend to decrease, while shrinkage becomes uncontrolled. According to Stephan Assie et al. (2007), SCC shows lower oxygen permeability, meaning better resistance to gas ingress compared to normal concrete. However, both SCC and conventional concrete exhibit similar resistance to aggressive agents and comparable reaction energy. Domone (2007), after analyzing over 70 cases, noted inconsistencies in the results due to the variety of materials, mix designs, and test methods used, while his 2006 case study offered practical insights into fresh concrete properties, mix proportions, and compressive strength. Domone also emphasized SCC's widespread application in concrete construction and its geographic evolution.

Brouwers & Radix (2005) demonstrated that a single admixture can produce the desired SCC properties without the need for additional agents to adjust viscosity. Corinaldesi and Moriconi (2004) found that cementitious materials, due to their porosity, have a slow chloride ion diffusion rate, which can be improved with hydrophobic materials. These materials also offer moderate resistance to freezing and thawing. Su et al. (2001) proposed a new SCC mix design with sand content in the range of 54-60% and water content between 170-176 kg/m³. Bertil (2001) conducted durability studies, concluding that the creep coefficient of SCC aligns with that of conventional concrete, and decreases as concrete strength increases.

Valeria has focused on developing durable Self-Compacting Concrete (SCC). Adding shrinkage-reducing admixture (SRA) results in a reduction in both yield stress and plastic viscosity. When CaO-based SRA is included, it improves the early-stage strength of the concrete. However, the worst strength outcomes are observed when SRA is combined with a hydrophobizing admixture. Mucteba and Mansur (2011) studied SCC's workability, hardened properties, and durability with different admixtures, noting that SCC mixed with fly ash performs well in workability tests. Specifically, a 25% fly ash replacement in Portland cement yielded better hardened property results. Filler materials also contribute to early strength in SCC mixes, and mineral admixtures improve SCC's resistance to sulfate attacks.

Heba (2011) extensively researched how curing conditions impact SCC with silica fume and fly ash, revealing that the optimal fly ash replacement is 30%. Substituting 10% of cement with silica fume showed better performance, improving strength by 10-12% over the fly ash mix. Aloia et al. (2006) pointed out that the dosage of Viscosity Enhancing Admixture (VEA) does not affect the superplasticizer saturation dosage, nor does it alter the rheological behavior of the cement paste. The slump flow values corresponded well with shear yield stress derived from vane geometry. Mustafa et al. (2006) also emphasized that fly ash, as a mineral admixture, significantly improves SCC's workability and shortens setting time.

According to the 2005 user manual for silica fume, proportioning and adjustments are crucial when using this material, and these guidelines were followed in determining the mix proportions for the current study. Bouzoubaa and Lachemi (2001) conducted research using high-volume fly ash, replacing 40-60% of the cement with fly ash. They found that compressive strength ranged from 26 to 48 MPa over 28 days, indicating that a cost-effective SCC could be developed with high fly ash content. However, they also noted a delayed setting time of three to four hours and a temperature reduction of 5-10%.

The inclusion of fibers in concrete significantly enhances both compressive strength and durability. Various studies, including those conducted by Kumar et al. in 1997, have developed statistical predictions and empirical models for compressive strength based on the Fiber Reinforcing Index (FRI), which is determined by the fiber's length and volume fraction. Their research showed that steel fiber reinforced concrete (SFRC) exhibits rapid increases in compressive strength with fiber content up to 1% by volume, after which the strength increase slows down. FRI plays a substantial role in determining compressive strength, and the authors proposed empirical relationships linking FRI to compressive strength.

Further studies by Faisal and Samir (1992) on the mechanical properties of high-strength fiber-reinforced concrete tested 154 specimens, achieving a compressive strength of 94 N/mm². They experimented with steel fiber volume fractions of 0.5%, 1.0%, and 1.5%. It was concluded that no significant issues with workability were encountered up to 1.5% fiber volume. Additionally, steel fibers improved the ductility and post-cracking load-bearing capacity of high-strength concrete. Their research proposed empirical relationships between fiber volume and the compressive strength of conventional concrete.

Balaguru and Shah (1992) noted that longer fibers, especially at higher volume fractions, can cause clumping during the mixing process, known as "balling," which negatively impacts the concrete's workability and strength. Similarly, Ziad and Paviz (1992) highlighted that the rheological properties of SFRC are crucial, as the large surface area and interlocking of fibers can lead to ball formation during mixing, affecting the hardened concrete's material properties.

Different types of steel fibers were also studied in relation to the properties of fresh concrete. It was found that the fiber reinforcing index (FRI) significantly affects fresh concrete’s workability. Crimped fibers provided slightly higher performance compared to plain fibers at a specific FRI. Ganesan and Ramana (1990) studied the stress-strain behavior of short, confined reinforced concrete columns with and without steel fibers. They used steel fibers with an aspect ratio of 70 and a volume fraction of 1.5%, concluding that lateral reinforcement slightly increases strain at peak loads, enhancing the concrete's performance under stress.

Cuenca and Serna (2013) studied the load deflection and shear properties of Steel Fiber Reinforced Self-Compacting Concrete (SFRSCC) precast beams, finding that steel fibers provided additional reinforcement alongside stirrups. The shear properties remained within the safe limits defined by codes. Steel fibers were effective in controlling crack formation and growth, leading to smaller and narrower cracks compared to beams without fibers. Additionally, steel fibers interacted positively with traditional transverse reinforcement, enhancing concrete's compressive solidifying capacity.

Research by Burcu & Tasdemir (2012) on Fiber Reinforced Self-Compacting Concrete (FRSCC) beams under static loading revealed that high-strength long steel fibers increased toughness and ductility compared to normal-strength fibers. While normal-strength fiber beams exhibited lower peak loads and steeper softening branches, high-strength fibers promoted more ductile behavior. The mode of failure also varied, with normal-strength fibers showing fiber pull-out, while fiber fracture dominated in other cases, highlighting the influence of fiber dispersion and alignment on mechanical properties.

Greeshma and Jaya (2007) conducted Finite Element Analysis (FEA) on a shear wall using ANSYS under seismic loading. The model used SOLID 65 elements for the shear wall and LINK 8 elements for reinforcements. The analysis, under both static and dynamic loading, further demonstrated how fiber-reinforced concrete could improve the behavior of shear walls.

Suji et al. explored the flexural behavior of reinforced fibrous concrete beams using synthetic fibers, specifically graded polypropylene fibers. Their study involved casting 1.8-meter-long reinforced concrete beams with varying fiber volume fractions of 0.1%, 2%, and 3%. The experimental results showed that while the crack patterns were consistent across all beams, the width and length of cracks decreased in fiber-reinforced concrete, demonstrating improved crack control.

Ganesan et al. tested SFRSCC beams' ultimate strength, using 1.2-meter-long reinforced concrete beams with steel fiber volume fractions of 0.25%, 0.5%, and 0.75%. Their results indicated that fiber-reinforced self-compacting concrete specimens exhibited superior strength and ductility compared to traditional concrete.

Thomas and Ramasamy (2006) studied partially prestressed concrete T-beams with steel fibers at various depths, utilizing M35, M65, and M85 mixes with a fiber volume fraction of 1.5%. They tested 3.85-meter-long T-beams under four-point bending and proposed analytical models for load-deflection and moment-curvature relationships, finding good agreement between experimental and analytical results.

Piti (2004) compared the toughness of steel and polypropylene fiber-reinforced concrete beams under bending, using ASTM C1018 and JSCE SF-4 standards. The study showed that steel fiber-reinforced concrete exhibited a single-peak response, while polypropylene fibers resulted in a double-peak response.
Similarly, Padmarajaiah & Ananth (2002) explored the flexural strength of prestressed high-strength concrete beams reinforced with steel fibers. Their research demonstrated that as fiber content increased, so did the toughness and ductility of the beams. Fully prestressed beams with 0.5%, 1.0%, and 1.5% steel fiber volume fractions saw maximum ductility increases of 18%, 45%, and 68%, respectively, with corresponding energy absorption increases of 25%, 78%, and 88%.

3 Materials

The materials utilized in the concrete mix play a crucial role in determining the overall performance and durability of the concrete. This section outlines the physical and chemical properties of the materials used, including cement, aggregates, admixtures, and their contributions to the concrete mix.

Cement

Ordinary Portland Cement (OPC) of 43 grade, conforming to IS 8112-1989, is employed in this study. The cement exhibits a standard consistency of 29.2%, an initial setting time of 45 minutes, a final setting time of 265 minutes, and a specific gravity of 3.15. The compressive strength values are 29 N/mm² at 3 days, 38.5 N/mm² at 7 days, and 48 N/mm² at 28 days, all exceeding the minimum requirements set by the relevant standards.

Fine Aggregate

Fine aggregate used in the concrete mix is produced from natural river sand, meeting the Zone II requirements of IS: 383-1970. Sieve analysis reveals a cumulative percentage weight passing of 99.6% for the 10 mm size and 0% for particles less than 150 µm. The fine aggregate has a specific gravity of 2.6, a fineness modulus of 2.83, water absorption of 0.75%, bulk density of 1654 kg/m³, and a free moisture content of 0.1%.

Coarse Aggregate

Coarse aggregates, sourced from local quarries, have a maximum size of 12.5 mm. They exhibit a specific gravity of 2.6, a fineness modulus of 2.73, and a water absorption of 0.5%. The bulk density is measured at 1590 kg/m³, with a free moisture content of 0.2%. The aggregate impact value is recorded at 11.2%, while the aggregate crushing value is 25.12%.

Water

Potable water, free from salts, is utilized for casting and curing, in accordance with the recommendations of IS: 456-2000.

Fly Ash

Class F fly ash collected from the Mettur Thermal Power Plant is included in the mix. It has a specific surface area of 3200 cm²/g, a specific gravity of 2.6, and a bulk density of 750 kg/m³.

Silica Fume

Silica fume, sourced from ELKEM materials in Mumbai, enhances the concrete's properties significantly. It has a specific surface area of 20.9 m²/g and a specific gravity of 2.2, contributing to improved durability and early strength.

Rice Husk Ash

Rice Husk Ash (RHA) obtained from Mufeed Rice Mill in Malappuram, Kerala, is finer than cement, with a specific gravity of 2.11 and a specific surface area of 3000 cm²/g. This material aids in filling voids and enhancing concrete performance.

Corrugated Steel Fibers

Corrugated steel fibers from Stewols India Pvt. Limited in Nagpur are utilized, characterized by a tensile strength of 1100 MPa and a diameter of 0.65 mm. These fibers are incorporated in various aspect ratios and volume fractions to improve the concrete's mechanical properties.

Superplasticizer

Conplast SP430 is employed as a superplasticizer to enhance the functionality of the concrete mix. It is based on sulphonated naphthalene polymers, has a specific gravity of 1.22, and provides approximately 1% air entrainment.

4. SEISMIC BEHAVIOUR OF SCC WITH OPTIMIZED FIBER CONTENT

4.1 General

This section discusses the detailing of reinforcement, test setup, details of specimens cast, and results of the structural properties of beams under static, forward cyclic, and reverse cyclic loading, as well as the results of beam-column joint specimens under static loading. Due to the lack of experimental facilities, the flexural tests are conducted as load-controlled tests.

4.2 Specimen Details

The experimental study comprises the casting and testing of 12 pairs of 2-meter-long reinforced concrete beams. Each beam is tested over a simply supported length of 1.8 m. Designed as under-reinforced sections, the beams are intended to withstand a minimum ultimate load of 30 kN. The details of the reinforcements in the test beams are shown in Figure 1. The tensile reinforcement consists of two 8 mm diameter bars at the bottom of the beam and two additional 8 mm diameter bars placed at the top. Stirrups with a diameter of 6 mm and a center-to-center distance of 100 mm are employed to secure the reinforcements and serve as shear reinforcements. The steel used for reinforcement is HYSD Fe 415. For each mix, three batches with a portion of 0.5% and an aspect ratio of 100 are prepared and tested under three loading scenarios.

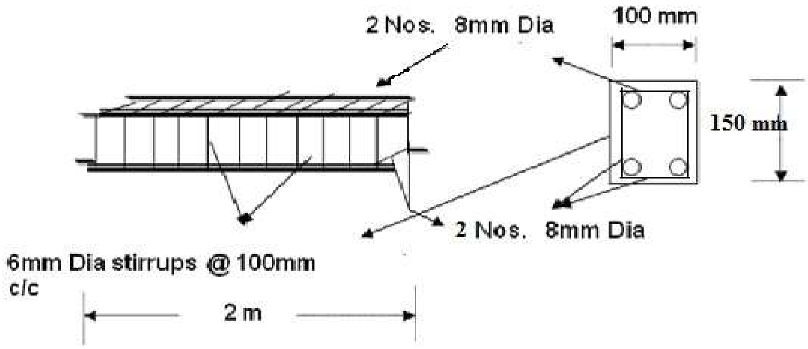

Figure 1: Reinforcement Detailing of Beam

4.3 Experimental Setup of Beams

Load tests are conducted at room temperature following Indian standards. Primary properties are determined by performing a center third loading test. Using a hydraulic jack with a capacity of 100 kN, the reinforced concrete beams with a span of 1.8 meters are subjected to four-point bending and middle third loading. The specimens are placed on a simply supported configuration of a 100 T Universal Testing Machine (UTM), and the beams are appropriately instrumented to measure deflections at mid-span using dial gauges.

4.4 Flexural Behavior of Beams Under Static Loading

The effects of adding discrete fibers on the flexural strength of reinforced concrete beams have been studied. The relationship between mid-span deflection and load has been derived from experiments on the beams. Critical seismic parameters such as ductility, energy absorption capacity, and stiffness degradation are evaluated at three key points: first cracking, first yielding, and ultimate load. Additionally, toughness indices for static loading are discussed.

4.4.1 Loading Sequence

Load is applied to the beams via a hydraulic jack with a capacity of 100 kN. Relevant mid-span readings are taken at each 2.5 kN loading interval, while cracking behavior along the beam's length is meticulously observed. The load and deflection values corresponding to the initial cracking of each beam are documented.

4.4.2 Load-Deflection Behavior

Figure 2 illustrates the load-mid span deflection curves for steel fiber-reinforced beams. The data indicate that the addition of fibers improves the behavior of beams at critical points, such as first cracking, first yielding, and ultimate load. The post-cracking and post-ultimate behaviors have also been enhanced. Key points of the load-deflection curves are summarized in Table 1. As the beams are designed as under-reinforced sections, the first yield occurs in the reinforcing steel. Following this, the beams are pushed toward the ultimate point. SCFSF3 demonstrates lower deflection compared to the other mixes at all stages. The deflections for SCFA1, SCFARH1, and SCFSFRH2 at first crack are 55%, 50%, and 20% greater than that of SCFSF3, respectively. Similarly, the final deflections for these three mixes are 108%, 134%, and 98% higher than SCFSF3.

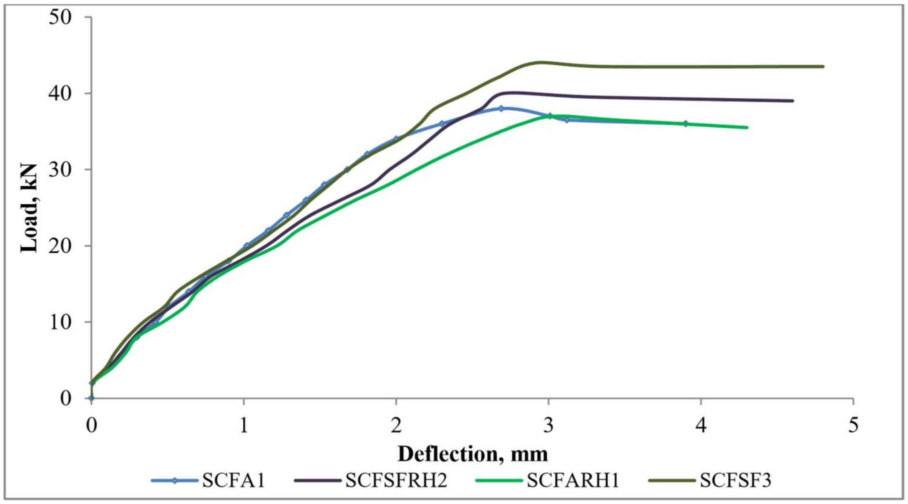

Figure 2: Load-Deflection Curve for Beams

Table 1: Salient Points of Load-Displacement Curves

Mix	**Pcr (kN)**	**δcr (mm)**	**P_u (kN)**	**δu (mm)**
SCFA1	10	0.4	38	2.6
SCFARH1	8	0.3	37	3.0
SCFSFRH2	13	0.6	40	2.7
SCFSF3	16	0.8	44	2.9

All beams failed in flexural mode due to yielding of the compressive steel. Cracking and spalling of concrete occurred following yielding for all beams. The closely spaced cracks in all fiber-reinforced concrete beams lead to reduced crack widths and enhanced neutral axis depth. The SCFSF3 mix demonstrated superior performance compared to other mixes, with SCFSFRH2 showing comparable results. The other two mixes exhibited similar outcomes. The enhanced load-diversion curve is directly associated with bond strength, significantly influencing the behavior of steel fibers after matrix cracking. The mix containing 20% silica fume yields better results across all loading stages due to its strong bonding capability. Conversely, the presence of rice husk ash in SCFSFRH2 did not provide a significant strength improvement when compared to SCFSF3, while SCFA1's lower strength attainment was affected by the bond between concrete and steel fibers.

4.4.3 Comparison of Critical Loads

Figure 3 demonstrates the significant difference between the ultimate load and first crack load for each of the four beams. The enhanced load-carrying capacity observed with fiber addition corroborates the improvement of load-bearing ability throughout the loading period. For the SCFSF3 mix, both the first crack load and ultimate load are markedly higher than those of the other three mixes. The inclusion of fibers in Self-Consolidating Concrete (SCC) enhances the load-carrying capacity, enabling the structure to withstand earthquakes more effectively.

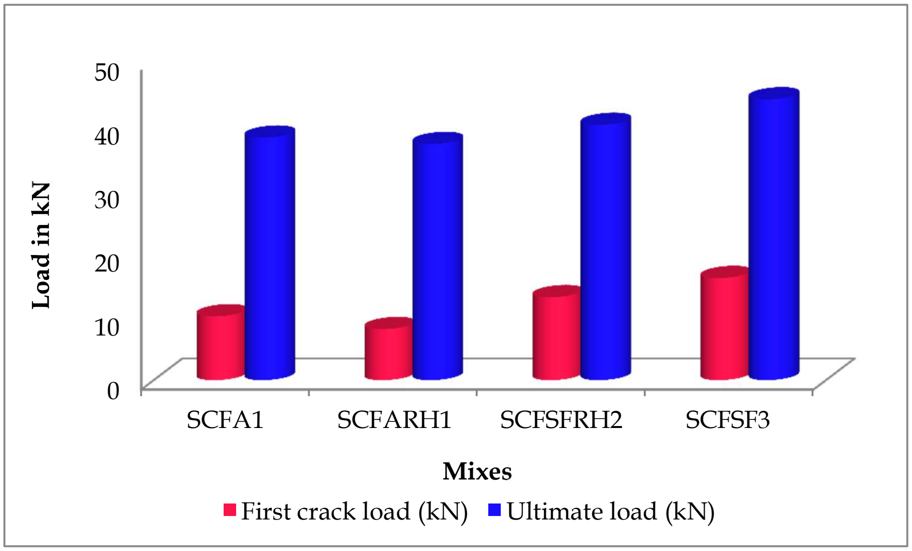

Figure 3: Comparison of Loads for Beams

4.4.4 Ductility and Energy Absorption Behavior

4.4.4.1 Ductility Factor

The ductility factor is defined as the ratio of ultimate deflection to first yield deflection. first yield is determined from the expected bilinear behavior of the beams. Table 6.2 presents the calculated ductility factor and energy absorption capacity for various SCC beam specimens based on experimental load-displacement curves.

Table 3: Ductility and Energy Absorption Parameters

Mix	Ductility factor (μ_d)	Energy absorption (kN-mm)
SCFA1	3.11	398
SCFARH1	3.14	421
SCFSFRH2	3.43	520
SCFSF3	4.1	598

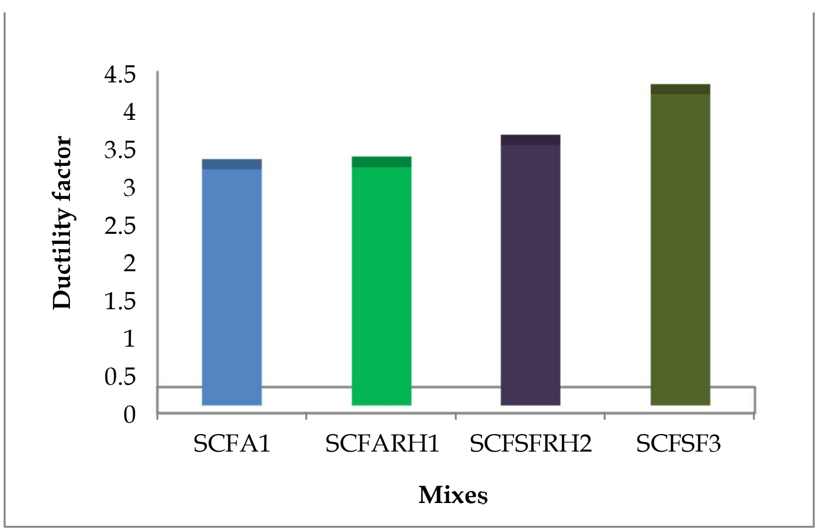

Figure 4: Comparison of Ductility Factor for SFRSCC Beams Under Static Loading

Figure 4 compares the ductility factors of four beam specimens. The SCFSF3 beam exhibits a ductility factor of 4.1. The SCFA1 beams have a ductility factor 24% lower than SCFSF3, while SCFARH1 and SCFSFRH2 have factors 24% and 16% lower, respectively, due to fiber slippage.

4.4.4.2 Energy Absorption

Energy absorption capacity is typically determined from the area under the load-deflection curve, reflecting the beam section's performance under flexural loading. As expected, the SCFSF3 concrete mix exhibits the highest energy absorption capacity, quantified at 598 kN-mm. When rice husk ash and fly ash are incorporated into concrete, only a limited increase in energy retention capacity is observed compared to SCFSF3, with SCFA1 and SCFARH1 fiber-reinforced concrete beams showing improvements of about 36% and 54%, respectively. The SCFSFRH2 beam demonstrates an energy absorption capacity of 520 kN-mm, approximately 94% of that of SCFSF3. The inclusion of fibers enhances post-cracking behavior, as indicated by the increased area under the load-deflection curve. This aligns with findings by Ganesan et al. (2006), which indicated that the ductility of fiber-reinforced beams improves by approximately 70% compared to conventional concrete.

4.4.5 Toughness Index

The toughness indices I5 and I10 are calculated based on the areas of the load-deflection curve up to displacements of 3 and 5.5 times the first crack deflection, divided by the area of the load-deflection curve up to the first crack deflection. The method follows ASTM C
1018 (1997) for evaluating toughness index values in fiber-reinforced concrete. The index values for various mixes are presented in Table 4. A comparison of toughness indices indicates that the addition of steel fibers significantly enhances toughness. The SCFSF3 mix exhibits the highest index value, while SCFA1 and SCFARH1 exhibit a relative decrease of 15% and 17% compared to SCFSF3, respectively.

Table 4: Toughness Indices of Specimens

Mix	**Pcr_EX (kN)**	**Pcr_FEA (kN)**	**Pcr_ EX / Pcr_ FEA**	**Pu_ EX (kN)**	**Pu_ FEA (kN)**	**Pu_ EX / Pu_ FEA**
SCFA1	10	12	0.83	38	42	0.90
SCFARH1	8	10	0.80	37	42	0.88
SCFSFRH2	13	15	0.86	40	46	0.86
SCFSF3	16	18	0.88	44	49	0.89

The significant difference between the toughness indices of the control mix and the fibers incorporated mix indicates a profound enhancement in toughness due to the inclusion of fibers.

4.5 Performance of Beam-Column Joint Specimens

The performance of beam-column joints is assessed based on their structural response under static loading conditions. The experimental test setup is similar to that of the beam specimens, with a configuration designed to facilitate observation of both flexural and shear responses.

4.6 Summary of Experimental Observations

The following observations can be drawn from the experimental results:
- The incorporation of steel fibers enhances the flexural strength and ductility of SCC beams, with SCFSF3 exhibiting the best performance across all loading conditions.
- The energy absorption capacity is significantly improved with fiber inclusion, with SCFSF3 yielding the highest capacity among the tested mixes.
- Toughness indices indicate that fiber-reinforced beams provide improved toughness compared to non-fiber mixes, making them more resilient under seismic conditions.
- Beam-column joint specimens also demonstrated satisfactory performance under static loads, indicating their

effectiveness in resisting flexural and shear forces.
These findings reinforce the potential of using fiber-reinforced self-consolidating concrete in seismic-resistant structures, providing valuable insights for future design and material selection.

5. Conclusion

Using the FEA software ANSYS, an analysis was conducted to compare the structural properties of reinforced concrete beams with fibers, focusing on aspects such as load-carrying capacity, ductility, energy absorption capacity, toughness index, and stiffness against an analytical model. The key conclusions from this analysis are as follows:

- The mix containing 20% fly ash and 20% silica fume demonstrates superior performance compared to the other three mixes tested
- For beams made with the SCFSF3 mix, the initial crack occurs later under static loading, forward cyclic loading, and both forward and reverse cyclic loading compared to the other three mixes.
- In terms of static loading conditions, the SCFSF3 mix exhibits higher toughness indices, load-carrying capacity, displacement ductility, and energy absorption capacity. The developed analytical model mirrors the results obtained from static loading tests closely.
- The SCFSF3 mix also shows improvements in load-carrying capacity, stiffness degradation behavior, displacement ductility, and energy absorption capacity under static, forward cyclic, and reverse cyclic loading conditions.
- The SCFSF3 beam-column joint outperforms the other three mixes regarding load-carrying capacity, displacement ductility, energy absorption capacity, and durability indices. The results from the comparison study using ANSYS are satisfactory, confirming the reliability of the findings.

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