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Sustainable Flexural Enhancement of Concrete-Filled Steel Tubular Beams Using Internal Curing Agents and Fabricated I-Section Reinforcement

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Abstract
This study investigates the flexural performance of Concrete-Filled Steel Tube (CFST) beams incorporating centrally embedded Fiber Glass Composite (FGC) I-sections and self-curing concrete using polyethylene glycol (PEG 400) admixture. Five concrete mixes with varying PEG 400 dosages (0-1.25% by cement weight) were optimized through comprehensive fresh and hardened properties testing, confirming optimum workability (80-100 mm slump, 500-600 mm flow), air content (<4%), and superior compressive (32.75 N/mm²), split tensile (3.69 N/mm²), and flexural (5.41 N/mm²) strengths at 28 days for the 1.25% mix compared to normal concrete. Two CFST beams—B1 (self-curing concrete) and B2 (normal concrete)—were subjected to four-point bending. Both beams exhibited high ultimate load capacity, stiffness, and ductility due to synergistic composite action between the steel tube, concrete core, and internal FGC I-section (88.9 × 38.1 × 4.67 mm). B1 demonstrated superior performance with minimal surface cracking, delayed yielding, better stiffness retention, and gradual localized indentation failure under loading points. The PEG 400 admixture ensured effective internal hydration within the sealed steel tube environment, promoting better microstructure development and steel-concrete bonding. Results confirm that the combination of steel confinement, internal FGC reinforcement, and self-curing concrete creates a structurally efficient flexural system with excellent energy dissipation and post-peak capacity. The study establishes PEG 400 at 1.0-1.25% dosage as optimal for CFST applications where external curing is impractical.
Keywords: Self-curing concrete, PEG 400, CFST beams, flexural performance, sustainability.

1. Introduction
Concrete remains the backbone of global construction, yet its conventional curing process demands substantial water resources—approximately 1-2 litres per kg of cement—exacerbating scarcity in regions like India where urban demand outstrips supply by 50% in cities such as Chennai and Coimbatore. Concrete-Filled Steel Tubular (CFST) systems offer superior structural efficiency through composite action, but the enclosed steel tube prevents external curing, compromising concrete hydration and long-term performance.This research addresses this critical gap by integrating Polyethylene Glycol (PEG 400) self-curing concrete within CFST beams reinforced with internal Fabricated Galvanized Channel (FGC) I-sections. PEG 400, a hydrophilic polymer, retains internal moisture for continuous hydration, eliminating external water needs while enhancing mechanical properties through reduced autogenous shrinkage and micro-cracking.

2. Literature Review
Yahia and Rashwan (2019) demonstrated that PEG 400 at 0.75% dosage achieved 39.2 MPa compressive strength (+22% vs. air-cured concrete) with 28% reduced drying shrinkage. Patel et al. (2017) identified 1.0% PEG 400 as optimal for M25 concrete, yielding 36.8 MPa compression (+18%) but cautioned against dosages exceeding 1.5% due to workability loss . Ibrahim (2015) reviewed self-curing agents, confirming PEG polymers prevent 30-40% autogenous shrinkage microcracks . Bentz and Snyder (2008) established internal curing principles using lightweight aggregates, while Kim et al. (2012) documented 25% crack resistance improvement through denser interfacial transition zones. For CFST flexural behavior, Tao et al. (2004) reported 2.5× ductility improvement with steel tubes carrying 70% tension zone stress and 35% concrete capacity enhancement . Fan and Lin (2017) achieved 42% moment capacity increase and 28% stiffness gain in I-section reinforced CFST beams . Ban and Lee (2017) demonstrated 45% flexural enhancement by positioning I-sections near tension faces . Zhao (2012) established CFST design guidelines showing confinement delays buckling for 25% slimmer sections . Zhan et al. (2019) quantified confinement effects with peak stress 1.8× unconfined concrete for 3-4 mm tubes . Shoukry and Kovacs (2003) modelled confined concrete with bilinear stress-strain behavior, 20-30% strength gain, and 50% ductility improvement.Mehta and Monteiro (2014) provided the microstructural foundation linking curing efficiency to mechanical performance , while Cook et al. (1992) quantified curing effects on concrete properties . Chen et al. (2021), Mohammed (2021), Gopalakrishnan (2021), Kumar and Singh (2020), and Wu and Nguyen (2016) further supported composite beam applications . Indian standards IS 456:2000, IS 10262:2019, and IS 2062:2011 governed material specifications [20-22]. Johnson (1994) established composite steel-concrete design principles.While these investigations validate individual technologies, this research addresses their novel integration—PEG 400 self-curing concrete, steel tube confinement, and internal FGC I-section reinforcement in flexural CFST beams—representing a significant advancement.

3. Applications:
The PEG 400-enhanced CFST beams offer excellent potential for seismic-resistant moment frames, long-span industrial trusses, bridge girders, high-rise building columns transitioning to beams, offshore platforms, and precast construction where external curing is challenging. The system's high ductility, confinement efficiency, and self-curing capability make it ideal for performance-based structural design in aggressive environments.

4. Materials and Properties
Ordinary Portland Cement (OPC) 53 Grade conforming to IS 12269:2013 served as the primary binder, selected for early strength development essential for CFST beam testing, with fresh cement stored in moisture-proof conditions. Manufactured Sand (M-sand) from high-grade granite and coarse aggregates (6 mm, 10 mm) optimized concrete matrix density, workability, and durability per Indian HPC practices. Polyethylene Glycol (PEG 400) acted as self-curing admixture at 0.75-1.25% dosages, retaining internal moisture for sustained hydration within sealed steel tubes. Fabricated Galvanized Channel (FGC) I-section (88.9 × 38.1 × 4.67 mm) provided primary tensile reinforcement, enhancing flexural capacity through composite action with confined concrete. Rectangular steel tube (83 × 145 × 2.8 mm, fy=250 MPa) served as permanent formwork, confinement system, and structural reinforcement, delaying buckling while improving ductility.

Figure:1 FGC I-Section.

Figure:2 Steel Tube Section

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5. Methodology

The mix design process adopted for M25 grade concrete and the procedure followed for casting and curing of specimens. Five different mixes were prepared, including conventional concrete mixes and self-curing mixes containing PEG 400.

The design of the concrete mix was carried out in accordance with IS 10262:2019 and IS 456:2000. The target mean strength was calculated considering a degree of quality control suitable for laboratory conditions.

The mix proportion was obtained and finalized through trial batching to achieve satisfactory workability and compaction.

6. MIX PROPORTIONS FOR M1 - M5

Table: 1 Mix Proportions for M1 - M5

MIX ID	M1	M2	M3	M4	M5
Cement (kg)	22.01	22.01	22.01	22.01	22.01
Fine aggregate (kg)	41.11	41.11	41.11	41.11	41.11
Coarse aggregate (kg)	70.40	70.40	70.40	70.40	70.40
Water (kg)	9.88	9.88	9.88	9.88	9.88
PEG 400 (%)	0.00%	0.00%	0.75%	1.00%	1.25%
PEG 400 (g)	0	0	165	220	275

6.1 Specimen Details

The specimen planning for this study was theoretically structured to ensure reliable statistical evaluation of the mechanical properties of each concrete mix. For every mix designation (M1–M5), a total of six cube specimens of size 150×150×150 mm were cast to determine compressive strength at different ages, thereby providing sufficient data points to capture variability within each mixture. In parallel, four cylinder specimens of size 150×300 mm were prepared for each mix to evaluate split tensile strength, enabling assessment of the concrete's tensile behavior, which is critical for understanding crack formation and propagation under service loads. Additionally, two prism specimens of size 100×100×500 mm were cast per mix to measure flexural strength through modulus of rupture testing, directly simulating bending conditions similar to those experienced by structural elements such as beams and slabs. Together, this theoretical specimen matrix (6 cubes, 4 cylinders, 2 prisms per mix) establishes a balanced and systematic experimental framework to compare the performance of normal, non-cured, and PEG-based self-curing concretes across compressive, tensile, and flexural response domains.

7. Casting and Curing

The ingredients for each mix were batch-weighed and blended in a drum mixer, with PEG 400 for the self-curing mixtures first dissolved in the gauged mixing water to ensure uniform dispersion. The fresh concrete was then placed into moulds in three successive lifts, and each layer was compacted using a standard tamping rod to limit entrapped air and achieve a dense matrix. For the M1 (normal curing) series, specimens were removed from the moulds after 24 hours and subsequently immersed in clean water until the respective test ages, whereas M2 (no curing) specimens were simply demoulded and stored in the laboratory without any further curing treatment. In the case of the self-curing mixes M3, M4, and M5, specimens were demoulded after 24 hours and left without external water curing, relying on the PEG 400 admixture to retain sufficient internal moisture to sustain the hydration process.

Figure 3 Preparation of Moulds

Figure 4 Mixing of Concrete

8. TRIAL MIX STRENGTH RESULTS

8.1 Compression Test

For the compression test, the study evaluated the capacity of concrete to resist crushing loads using 30 cube specimens of size 150×150×150 mm cast from the five mixes. Each cube was positioned centrally between the platens of a compression testing machine, and load was applied gradually until visible cracking and eventual failure occurred, with the corresponding peak load recorded for each specimen. Compressive strength was then computed as the ratio of peak load to loaded surface area, and the 7-day and 28-day results were tabulated (Table:2) to compare the influence of PEG 400 dosage on early and later age strength development across mixes M1–M5.

Figure 5 Compression Test

Table:2 Compressive Strength Results

Mix	PEG 400 (%)	7-day average load (N/mm²)	28-day average load (N/mm²)
M1	0.00	18.77	30.89
M2	0.00	13.41	21.08
M3	0.75	16.45	29.25
M4	1.00	18.13	31.66
M5	1.25	21.63	32.75

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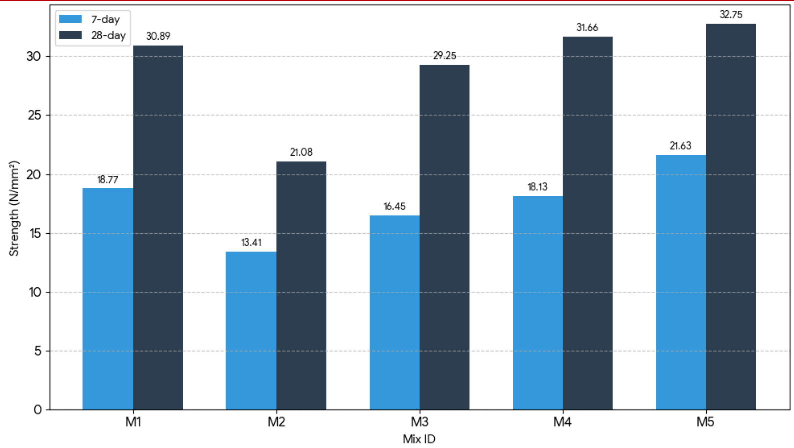

Chart 1: Compressive Strength Results

8.2 Split Tensile Test

In the split tensile test, the tensile behavior of concrete—known to be brittle and weak in direct tension—was assessed indirectly using 20 cylindrical specimens of 150 mm diameter and 300 mm height. Each cylinder was placed horizontally in the compression testing machine so that the vertical compressive load produced a uniform tensile stress along the vertical diameter, and the load at first cracking and at failure was recorded for three specimens per mix. The split tensile strength was calculated using the expression Split Tensile Strength $=2P/\Pi DL$ where P is the peak load in kN, D is the diameter in mm, and L is the length of the cylinder in mm, and the 7-day and 28-day strengths were compiled in Tables 3 for all mixes.

Figure 6 Split Tensile Test

Table:3 Split Tensile Strength Results

Mix	PEG 400 (%)	7-day avg (N/mm²)	28-day avg (N/mm²)
M1	0.00	2.29	3.36
M2	0.00	1.69	2.15
M3	0.75	1.57	2.87
M4	1.00	2.04	3.39
M5	1.25	2.40	3.69

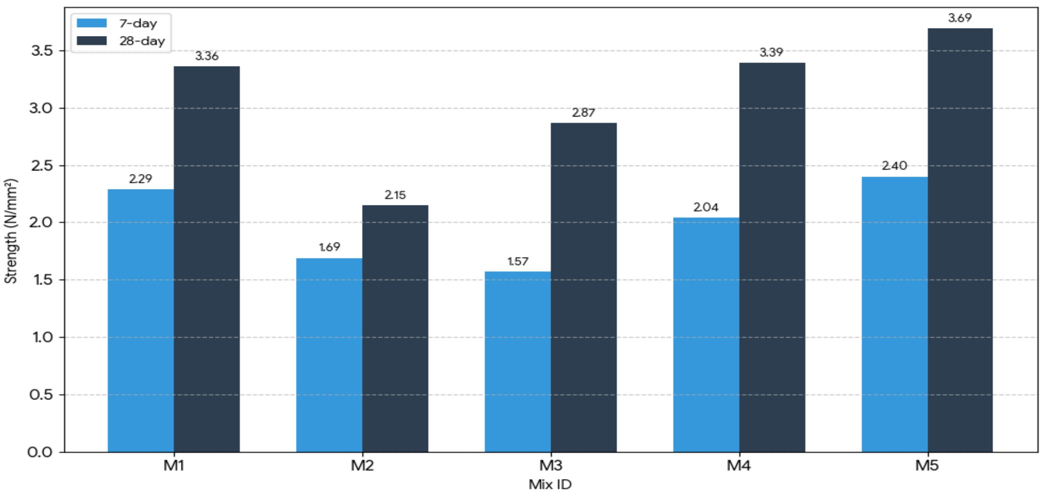

Chart 2: Split Tensile Strength

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8.3 Flexural Strength Test

For the flexural strength test, the resistance of concrete to bending was examined using prism specimens of size 100×100×500 mm tested under two-point loading in a flexure testing machine. The prisms were simply supported over an effective span of 400 mm, with loading points positioned at one-third span from each support to create a constant moment region and reduce shear effects, and the load was applied gradually until cracks initiated at the tension face at mid-span and propagated to failure. The modulus of rupture (flexural strength) was calculated from the recorded peak load using the standard bending equation $\textbf{Flexural Strength (f\_r)} = \frac{P \cdot L}{b \cdot d^2}$, where P is the peak load (N), L is the span(mm), b is the width(mm), and d is the depth of the prism(mm), and the outcomes for 7-day and 28-day tests were summarized in Tables 4. Plotting these results as bar charts or line graphs with flexural strength against mix ID for both ages provides a clear visual representation of the enhancement in bending capacity achieved by the PEG 400 self-curing mixes compared with conventional curing and no-curing conditions.

Figure 7 Flexural Strength Test

Table:4 Flexural Strength Results

Mix	PEG 400 (%)	7-day flexural (N/mm²)	28-day flexural (N/mm²)
M1	0.00	4.05	5.12
M2	0.00	2.335	2.505
M3	0.75	3.475	4.155
M4	1.00	4.03	5.08
M5	1.25	5.05	5.41

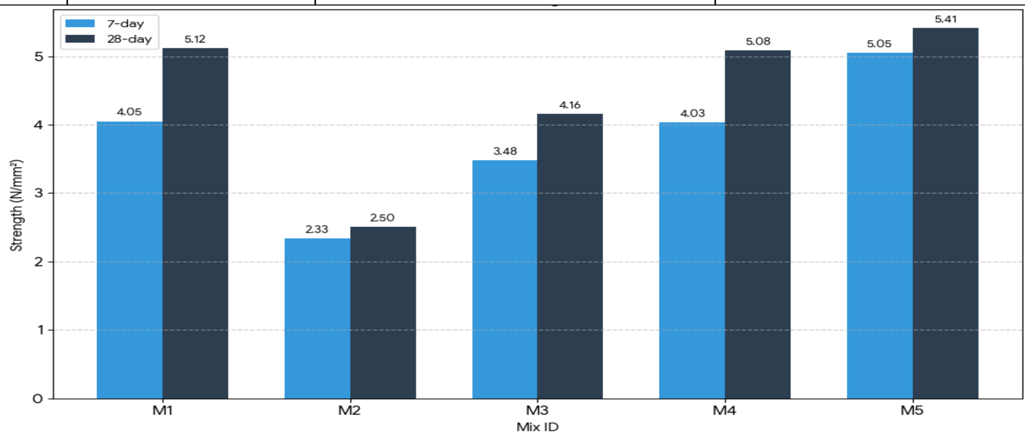

Chart 3: Flexural Strength Results

9. Result and Discussion for Materials

The test results show that using PEG 400 as a self-curing agent improves overall mechanical performance of concrete at both 7 and 28 days, with the best behavior around 1.0–1.25% dosage by weight of cement.

9.1 Compressive strength behavior

- For compressive strength, mixes with PEG 400 (M3–M5) reach higher 7-day strengths than the control concrete, indicating better early-age hydration under limited external curing.
- At 28 days, the mix with 1.25% PEG 400 (M5) attains the highest average compressive strength, followed closely by 1.0% PEG (M4), showing that excess PEG beyond this level is not required and 1.0–1.25% can be treated as an optimum range for strength.

9.2 Tensile strength behavior

- Split tensile strength at 7 days is low for the non-PEG mixes and improves notably for M4 and M5, implying that PEG helps in reducing micro-cracking due to better internal moisture availability.
- By 28 days, all PEG mixes gain tensile strength, with M5 again giving the maximum value, which is significantly higher than the normal water-cured control, confirming better development of the bond within the cement matrix.

9.3 Flexural strength behavior:

- Flexural strength at 7 days increases with PEG dosage; the 1.25% mix (M5) shows the highest modulus of rupture, which is important for pavements and slabs subjected to bending.
- At 28 days, PEG mixes retain or slightly enhance this advantage, with M3–M5 all performing better than the control, indicating improved toughness and crack-resistance under flexure.

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10. Structural Engineering interpretation

- From a structural engineering point of view, PEG 400 as a self-curing admixture provides a practical method to achieve or exceed the strength of conventionally cured concrete where external curing is difficult, such as congested reinforcement, vertical members, or hot climates.
- Considering strength gain in compression, tension, and flexure together, a PEG 400 dosage of about 1.0–1.25% is recommended as an optimum level for M-grade concrete in this study, balancing mechanical performance with material economy and constructability.

11. Beam Casting and Instrumentation

Table:5 Beam Dimensions And Configuration

Description	B1 (CFST-SC)
CFST beam with self-curing concrete	
Overall size (mm)	83 × 145 × 1000
Steel tube thickness	2.8 mm
Internal reinforcement	FGC I-section

The FGC I-section (88.9 mm × 38.1 mm × 4.67 mm) was positioned centrally within the steel tube to act as the primary flexural reinforcement in the composite beams, thereby enhancing moment resistance, bending stiffness, crack distribution, and ductility under loading. To ensure full composite action, the I-section was completely embedded in the concrete core; casting involved first securing the FGC section inside the tube using temporary spacers, followed by pouring self-curing concrete (optimum PEG 400 mix for B1) from one end to minimize air entrapment, with a steel rod employed for thorough compaction along the beam length. Unlike conventional curing, no external water curing was applied to B1 (CFST-SC), as the PEG 400 admixture provided internal moisture retention for sustained hydration. Similarly it was compared with B2 (CFST-NC) used conventional M25 concrete which was water cured for the standard curing period.

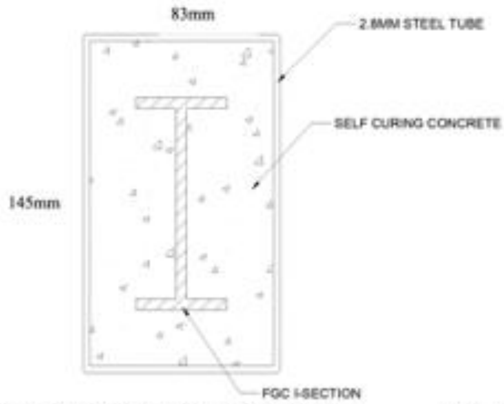

Figure 8.1 CFST Beam Cross Section Details


Figure 8.2 Placement of FGC I-Section


Figure 8.3 Before Casting of Beams


Figure 8.4 Casting of CFST Beams


Figure 8.5 Four-Point Bending Test Setup Normal CFST Beam

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Figure 8.5 Four-Point Bending Test Setup Normal CFST Beam

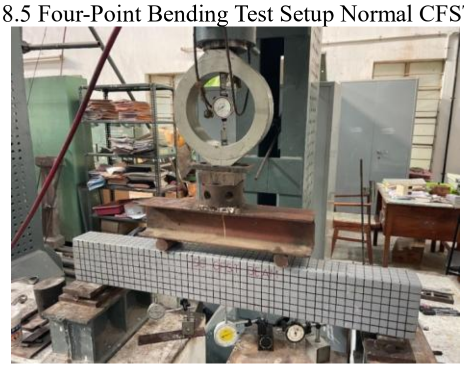

Figure 8.6 Four-Point Bending Test Setup SC CFST Beam

Figure 8.7 Failure Pattern of SC CFST Beam

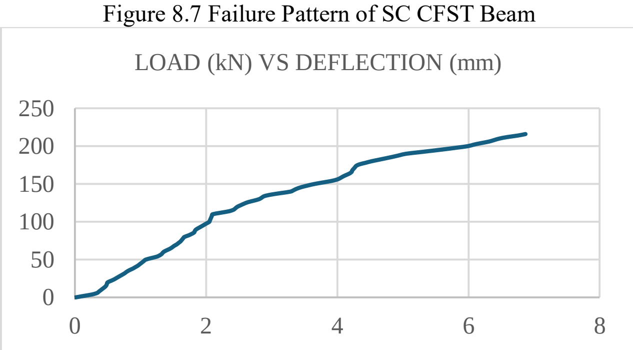

Chart 4: Load VS Deflection for SC CFST

Figure 8.8 Failure Pattern of Normal CFST Beam

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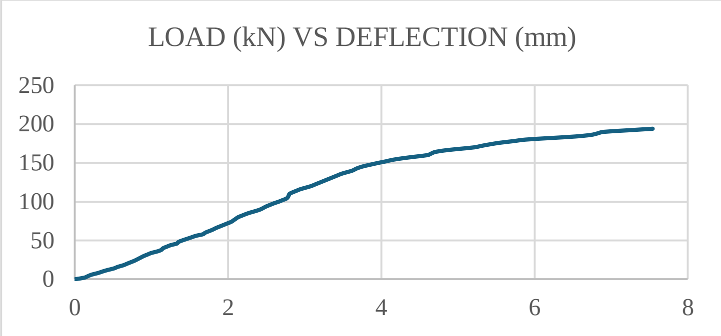

Chart 5: Load VS Deflection for Normal CFST

Table 6: Flexural Test Results

Beam Type	Ultimate Load (kN)	Deflection (mm)
SC CFST	216	6.87
CFST	195	7.54

12. Result and Discussion for Beam

12.1 Ultimate Load Capacity

The CFST beams demonstrated significantly higher ultimate load-carrying capacity due to the synergistic composite action between the steel tube, internal FGC I-section, and concrete core. Self-curing concrete in B1 (CFST-SC) further enhanced this performance over B2 (CFST-NC), confirming the benefits of PEG 400 admixture in promoting internal hydration and superior mechanical properties.

12.2 Crack Propagation Patterns

1. B1 (CFST-SC) exhibited failure initiation near loading points due to localized compression between the steel tube and loading roller, rather than mid-span flexure. The self-curing concrete core remained well-confined with minimal surface cracking, indicative of effective internal moisture retention by PEG 400 that supported sustained hydration and microstructure development. This resulted in gradual failure progression and high post-peak ductility, maintained through robust composite interaction among the steel tube, concrete, and FGC I-section.
2. B2 (CFST-NC) showed similar localized compression failure at loading points but with wider surface cracks and accelerated stiffness degradation compared to B1. The lack of internal curing agents led to suboptimal hydration within the confined concrete core, reducing compressive/tensile capacities and steel-concrete bond strength, which contributed to earlier failure and lower ductility.

12.3 Comparative Performance Analysis

The superior behavior of B1 over B2 validates the self-curing mechanism: PEG 400 ensured better microstructure development, higher compressive/tensile strengths (as evidenced by prior cube/prism tests), and enhanced interfacial bonding with steel elements. These factors delayed crack propagation, improved energy dissipation, and increased overall structural efficiency, making PEG 400-CFST beams particularly suitable for applications requiring high ductility and confinement.

12.4 Overall Experimental Observations

The experimental investigation highlights the influence of self-curing concrete, steel confinement, and internal FGC I-section reinforcement on the flexural behavior of CFST beams. Under four-point bending, both CFST beams exhibited strong composite interaction, with primary failure occurring through localized indentation and crushing under loading points rather than typical mid-span crack propagation. Notably, the SC CFST beam (B1) displayed smaller surface deformation, delayed yielding, better stiffness retention, and higher load-carrying capacity compared to B2, demonstrating the clear advantages of PEG 400 in closed tubular environments where external curing is impractical.

Conclusion

This study investigated the flexural behavior of Concrete-Filled Steel Tube (CFST) beams incorporating an internal FGC I-section and self-curing concrete using PEG 400 admixture. The self-curing mechanism enabled effective internal hydration within the sealed steel tube environment where conventional external curing proves impractical. Trial mix optimization confirmed that the PEG 400 dosage yielding superior compressive, split tensile, and flexural strengths compared to normal concrete.

Beam tests revealed that the CFST beam with self-curing concrete and internal I-section (B1) achieved the highest ultimate load capacity, enhanced stiffness, and reduced deflection throughout loading. The centrally positioned FGC I-section (88.9 × 38.1 × 4.67 mm), serving as primary flexural reinforcement, significantly boosted tensile resistance and delayed crack propagation. Both CFST beams (B1 and B2) demonstrated gradual failure characterized by localized indentation beneath loading points rather than brittle mid-span cracking, exhibiting excellent energy absorption and substantial post-peak load retention.

12.5 Key Findings

Internal FGC I-section placement enhanced moment resistance, stiffness, and crack control through improved tensile capacity near the tension zone.

Self-curing concrete with PEG 400 markedly improved hydration efficiency, microstructure development, and steel-concrete interfacial bonding in confined spaces.

CFST beams exhibited ductile failure modes with high post-deflection strength, contrasting sharply with conventional reinforced concrete behavior.

The synergistic combination of steel tube confinement, internal steel reinforcement, and self-curing concrete creates a structurally efficient flexural system suitable for high-performance applications requiring ductility and durability.

12.6 Future Scope

Based on the research outcomes, several promising directions warrant further investigation to expand the practical application of PEG 400-enhanced CFST beams with internal FGC I-sections:

- I-Section Optimization: Examine varying I-section positions and depths within the steel tube, particularly closer to the tension face, to maximize flexural resistance, ductility, and moment capacity.

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- Alternative Curing Agents: Conduct comparative studies of PEG 400 against other internal curing agents or mineral admixtures to achieve cost-effective hydration while preserving mechanical performance.
- Cyclic/Seismic Performance: Evaluate CFST beams under repeated or reversed loading to assess their suitability for earthquake-resistant structures and fatigue-prone applications.
- Numerical Validation: Develop Finite Element Models (ABAQUS/ANSYS) to predict stress distribution, crack propagation, and ultimate capacity, validating and extending experimental results.
- Full-Scale Testing: Test longer span or continuous beam configurations to establish design guidelines for industrial, bridge, and high-rise building applications.
- Durability Assessment: Investigate fire resistance, corrosion behavior, and long-term durability under service conditions to support robust structural design codes.

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