

# Chloride Penetration Resistance of Hybrid Fibre Reinforced SCC

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## ABSTRACT

Self-compacting concrete (SCC) offers high flowability and consolidation under its own weight, but cracking and connected pore pathways can accelerate chloride ingress in aggressive environments. This investigation evaluated the fresh, mechanical, and chloride-resistance performance of M40 SCC reinforced with hooked-end steel fibres and polypropylene microfibres. A control mixture (SCC-C) was compared with HF-SCC1, HF-SCC2, and HF-SCC3 containing steel/polypropylene fibre contents of 0.5/0.1%, 0.75/0.15%, and 1.0/0.2%, respectively. Fresh properties were assessed using slump flow, T50 flow, V-funnel, and L-box tests; hardened performance was measured by compressive, split-tensile, and flexural strength; and durability was evaluated through chloride penetration depth and rapid chloride penetration testing. All mixtures remained within the reported EFNARC acceptance ranges, although increasing fibre content reduced flowability. HF-SCC2 achieved the highest 28-day compressive, split-tensile, and flexural strengths of 53.4, 4.96, and 6.78 MPa, corresponding to improvements of 14.84%, 28.83%, and 30.38% over SCC-C. It also recorded the lowest chloride penetration depth (10.8 mm) and RCPT charge (1580 coulombs), representing reductions of 41.62% and 44.56%. The results identify HF-SCC2 as the optimum mixture, providing the best balance between SCC workability, mechanical strength, and chloride resistance.

**Keywords:** Self-compacting concrete; Hybrid fibres; Steel fibre; Polypropylene fibre; Chloride penetration; RCPT

## I. INTRODUCTION

Chloride ingress is a major durability concern in reinforced concrete exposed to marine, coastal, and salt-laden environments. Chloride ions migrate through capillary pores and cracks, disrupt the protective passive layer around reinforcement, and promote corrosion, cracking, spalling, and progressive loss of structural performance. Studies reported in the thesis show that crack width and connected transport pathways strongly influence chloride penetration and corrosion risk [4]-[6].

Self-compacting concrete was developed to flow through congested reinforcement and achieve consolidation without external vibration. Its performance depends on filling ability, passing ability, viscosity, and segregation resistance. Although SCC can produce dense and uniform concrete, its long-term chloride resistance remains sensitive to permeability and crack formation, making crack control and mix optimization essential.

Hybrid fibre reinforcement combines fibres that operate at different crack scales. Polypropylene microfibres restrict early microcracks and shrinkage-related discontinuities, whereas steel fibres bridge larger cracks and enhance toughness. The literature reviewed in the thesis indicates that hybrid fibre systems can improve crack control, mechanical performance, and resistance to chloride transport [1]-[3].

The present study therefore compares a control SCC mixture with three steel-polypropylene hybrid-fibre mixtures. The investigation follows the proof chain from material selection and M40 mix design to fresh-property testing, mechanical-strength evaluation, chloride-resistance testing, and selection of an optimum mixture.

## II. OBJECTIVES

- To formulate and validate optimized proportions for M40 self-compacting concrete by balancing binder content, aggregate packing, water-cement ratio, and superplasticizer dosage.
- To evaluate filling ability, viscosity, passing ability, and segregation resistance through slump flow, T50 flow, V-funnel, and L-box measurements.
- To determine the influence of hybrid steel and polypropylene fibres on compressive, split-tensile, and flexural strength.
- To quantify chloride penetration depth and RCPT charge for hybrid-fibre SCC relative to the unreinforced control.
- To identify the fibre dosage that provides the best balance of workability, mechanical performance, and chloride resistance.

### III. LITERATURE SURVEY

Cao, Zhang, and co-authors examined fibre-reinforced self-consolidating concrete under chloride and frost exposure and reported that hybrid fibres restricted crack development and reduced chloride ingress [1]. Bhogone and Subramaniam similarly associated the combined action of steel and polypropylene fibres with improved multi-scale crack control and lower chloride penetration [2].

Hari and Mini evaluated hybrid-fibre high-strength SCC and found that fibre addition could reduce workability while improving tensile, flexural, and durability-related performance when the dosage remained within a practical range [3]. These observations support the need to assess the workability-strength trade-off rather than selecting a mixture only on the basis of fibre content.

Geiker emphasized the relationship between cracks, chloride ingress, and reinforcement corrosion, while Sahmaran and Li and Maalej and Quek reported that crack characteristics and fibre-enabled crack control influence chloride transport in cementitious composites [4]-[6]. Together, the reviewed studies provide the basis for testing steel-polypropylene hybrid fibres as a means of reducing transport pathways in SCC.

### IV. MATERIALS AND METHODOLOGY

#### Experimental programme

The laboratory programme compared conventional SCC with three hybrid fibre-reinforced SCC formulations under identical material preparation, casting, curing, and testing conditions. The sequence comprised material selection, material-property testing, SCC mix design, preparation of the control and hybrid mixes, casting and curing, fresh-concrete tests, mechanical-strength tests, chloride-penetration tests, and comparative analysis.



Fig. 1. Experimental methodology adopted in the investigation.

#### Materials

OPC 53-grade cement was used with Zone II natural river sand and 10 mm crushed angular coarse aggregate. Potable water and a polycarboxylate ether-based high-range water-reducing admixture were used to obtain SCC flowability. Hooked-end steel fibres and polypropylene microfibres provided the hybrid reinforcement. Aggregate and concrete materials were selected with reference to the standards reported in the thesis [7]-[9].

Table 1. Materials used in the study

| Sl. No. | Material       | Description                         | Relevant standard |
|---------|----------------|-------------------------------------|-------------------|
| 1       | Cement         | Ordinary Portland Cement (53 Grade) | IS 12269          |
| 2       | Fine aggregate | Natural river sand (Zone II)        | IS 383            |

| Sl. No. | Material            | Description                       | Relevant standard          |
|---------|---------------------|-----------------------------------|----------------------------|
| 3       | Coarse aggregate    | Crushed angular aggregate (10 mm) | IS 383                     |
| 4       | Water               | Potable water                     | IS 456                     |
| 5       | Superplasticizer    | Polycarboxylate ether-based HRWR  | Manufacturer specification |
| 6       | Steel fibre         | Hooked-end steel fibre            | ASTM standards             |
| 7       | Polypropylene fibre | Synthetic microfibre              | ASTM standards             |

**Table 2. Properties of the hybrid fibres**

| Property         | Steel fibre | Polypropylene fibre  |
|------------------|-------------|----------------------|
| Type             | Hooked-end  | Synthetic microfibre |
| Length           | 30 mm       | 12 mm                |
| Diameter         | 0.5 mm      | 0.03 mm              |
| Aspect ratio     | 60          | 400                  |
| Specific gravity | 7.85        | 0.91                 |
| Tensile strength | 1100 MPa    | 400 MPa              |

**Table 3. Properties of the superplasticizer**

| Property           | Value                   |
|--------------------|-------------------------|
| Type               | Polycarboxylate ether   |
| Specific gravity   | 1.08                    |
| Physical state     | Liquid                  |
| Chloride content   | Nil                     |
| Recommended dosage | 0.5-2% by cement weight |

### Mix design and mixture combinations

The M40 concrete mixture was proportioned using the procedure stated in the thesis as IS 10262:2019. The adopted water-cement ratio was 0.38. Water content was reduced to 160 L/m<sup>3</sup> through the use of superplasticizer, giving a cement content of approximately 421 kg/m<sup>3</sup>. The same base matrix was used to compare the control and hybrid-fibre mixtures.

**Table 4. Final mix proportion for 1 m<sup>3</sup> of concrete**

| Material                 | Quantity         |
|--------------------------|------------------|
| Cement                   | 421 kg           |
| Water                    | 160 L            |
| Fine aggregate           | 820 kg           |
| Coarse aggregate (10 mm) | 980 kg           |
| Superplasticizer         | 1-1.5% of cement |
| Water-cement ratio       | 0.38             |

**Table 5. Hybrid fibre-reinforced SCC mixture combinations**

| Mix ID  | Steel fibre (%) | Polypropylene fibre (%) | Description            |
|---------|-----------------|-------------------------|------------------------|
| SCC-C   | 0               | 0                       | Control SCC            |
| HF-SCC1 | 0.5             | 0.1                     | Hybrid fibre SCC mix 1 |
| HF-SCC2 | 0.75            | 0.15                    | Hybrid fibre SCC mix 2 |

| Mix ID  | Steel fibre (%) | Polypropylene fibre (%) | Description            |
|---------|-----------------|-------------------------|------------------------|
| HF-SCC3 | 1.0             | 0.2                     | Hybrid fibre SCC mix 3 |

### Specimen preparation and testing

Materials were batched and mixed to obtain a uniform SCC matrix. Fibres were introduced gradually to limit clustering and promote dispersion. Specimens were cast without external vibration, finished, demoulded after the initial setting period, and water-cured. Fresh tests were conducted immediately after mixing, and hardened specimens were tested at the curing ages reported in the thesis.

**Table 6. Test matrix and specimen details**

| Test                      | Purpose                                 | Specimen/type  | Size or reported basis |
|---------------------------|-----------------------------------------|----------------|------------------------|
| Slump flow                | Flowability and filling ability         | Fresh concrete | EFNARC procedure       |
| T50 flow                  | Viscosity assessment                    | Fresh concrete | Time to 500 mm spread  |
| V-funnel                  | Flow time and segregation resistance    | Fresh concrete | EFNARC procedure       |
| L-box                     | Passing ability                         | Fresh concrete | Height ratio           |
| J-ring                    | Passing ability and blocking resistance | Fresh concrete | Reported as conducted  |
| Compressive strength      | Load-carrying capacity                  | Cube           | 150 × 150 × 150 mm     |
| Split-tensile strength    | Indirect tensile behaviour              | Cylinder       | 150 × 300 mm           |
| Flexural strength         | Bending resistance                      | Prism          | 100 × 100 × 500 mm     |
| Chloride penetration/RCPT | Resistance to chloride-ion ingress      | Cylinder/disc  | Standard size          |



**Fig. 2. Compressive-strength and split-tensile-strength test arrangements reported in the thesis.**

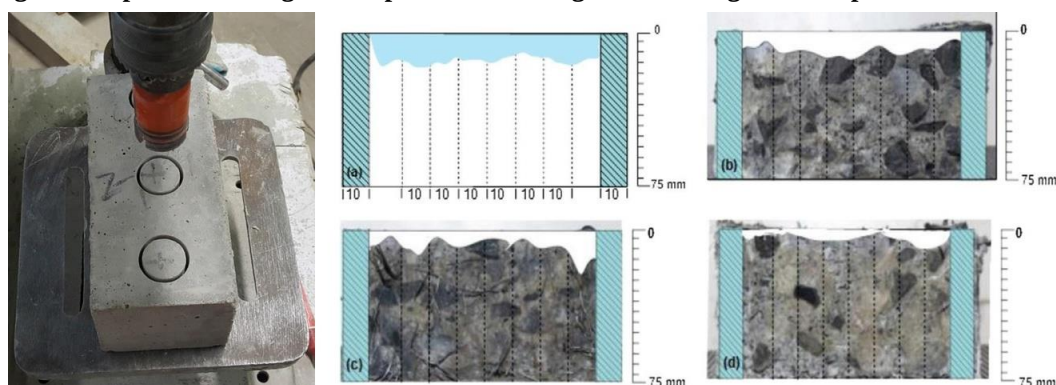


**Fig. 3. Chloride-test specimen preparation and silver-nitrate measurement of penetration depth.**

## V. RESULTS AND DISCUSSION

### Fresh properties

Hybrid fibre addition progressively reduced free flow and increased the time required for concrete movement. Slump flow decreased from 745 mm for SCC-C to 655 mm for HF-SCC3, while T50 and V-funnel times increased from 2.4 to 4.1 s and from 7.8 to 11.2 s, respectively. The L-box ratio decreased from 0.95 to 0.82 as fibre content increased. These changes reflect greater internal resistance and fibre-particle interaction.

**Table 7. Fresh properties of the SCC mixtures**

| Mix ID  | Slump flow (mm) | T50 flow (s) | V-funnel (s) | L-box ratio |
|---------|-----------------|--------------|--------------|-------------|
| SCC-C   | 745             | 2.4          | 7.8          | 0.95        |
| HF-SCC1 | 720             | 2.9          | 8.6          | 0.91        |
| HF-SCC2 | 690             | 3.4          | 9.7          | 0.87        |
| HF-SCC3 | 655             | 4.1          | 11.2         | 0.82        |

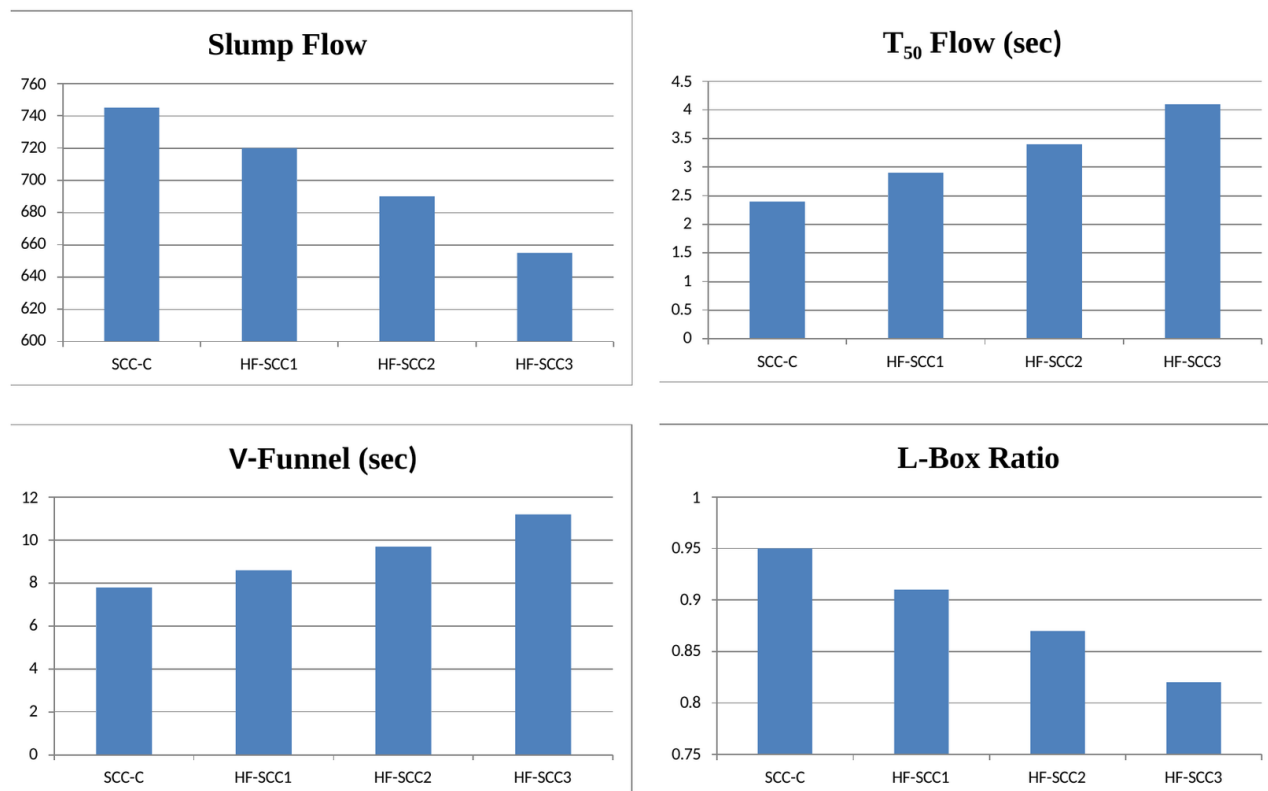


**Fig. 4. Slump flow, T50 flow, V-funnel, and L-box results for the control and hybrid-fibre mixtures.**

**Table 8. EFNARC acceptance comparison reported in the thesis**

| Parameter   | EFNARC range | Observed status |
|-------------|--------------|-----------------|
| Slump flow  | 650-800 mm   | Acceptable      |
| T50 flow    | 2-5 s        | Acceptable      |
| V-funnel    | 6-12 s       | Acceptable      |
| L-box ratio | 0.80-1.00    | Acceptable      |

All measured fresh properties remained within the acceptance ranges reported in the thesis. HF-SCC2 maintained a slump flow of 690 mm, a T50 time of 3.4 s, a V-funnel time of 9.7 s, and an L-box ratio of 0.87, demonstrating that the optimum-strength mixture retained the required SCC behaviour.

## Mechanical properties

The hybrid fibres improved compressive, split-tensile, and flexural performance up to the HF-SCC2 dosage. The 28-day compressive strength increased from 46.5 MPa for SCC-C to 53.4 MPa for HF-SCC2. Split-tensile strength increased from 3.85 to 4.96 MPa, and flexural strength increased from 5.20 to 6.78 MPa. The slightly lower values recorded by HF-SCC3 indicate that excessive fibre content reduced the benefit, probably through the workability and compaction effects described in the thesis.

**Table 9. Mechanical-strength results**

| Mix ID  | 7-day compressive (MPa) | 28-day compressive (MPa) | 28-day split-tensile (MPa) | 28-day flexural (MPa) |
|---------|-------------------------|--------------------------|----------------------------|-----------------------|
| SCC-C   | 32.8                    | 46.5                     | 3.85                       | 5.20                  |
| HF-SCC1 | 35.2                    | 49.8                     | 4.42                       | 6.05                  |
| HF-SCC2 | 37.6                    | 53.4                     | 4.96                       | 6.78                  |
| HF-SCC3 | 36.4                    | 51.2                     | 4.78                       | 6.51                  |

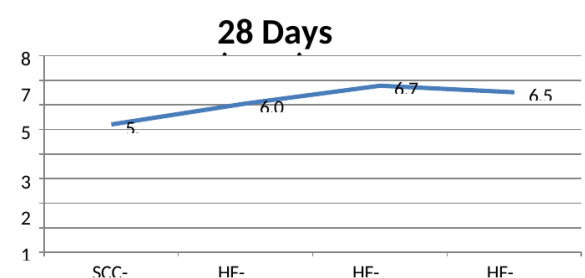
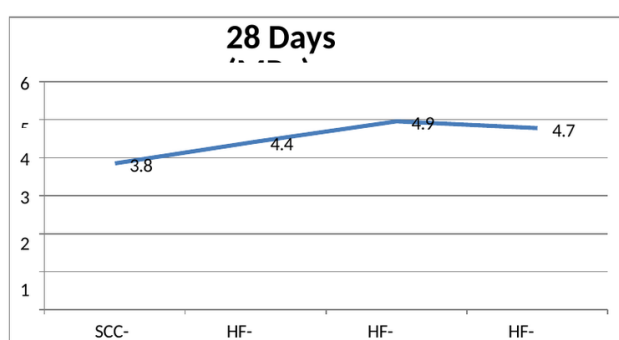


**Fig. 5. Twenty-eight-day split-tensile and flexural-strength comparisons.**

**Table 10. Percentage improvement in mechanical properties for the best hybrid mixture**

| Property               | SCC-C    | Best hybrid mix | Improvement |
|------------------------|----------|-----------------|-------------|
| Compressive strength   | 46.5 MPa | 53.4 MPa        | 14.84%      |
| Split-tensile strength | 3.85 MPa | 4.96 MPa        | 28.83%      |
| Flexural strength      | 5.20 MPa | 6.78 MPa        | 30.38%      |

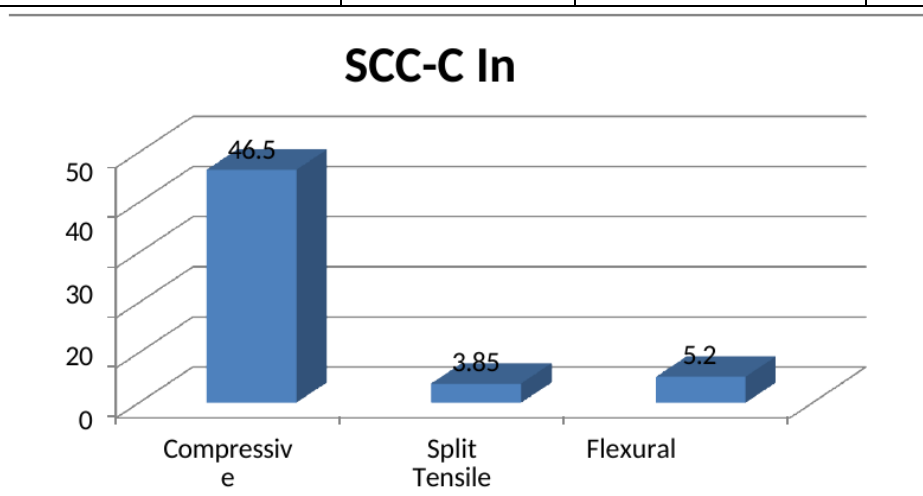


**Fig. 6. Mechanical-performance chart retained from the thesis result section.**

The improvement was most pronounced in flexural and split-tensile strength, supporting the thesis interpretation that steel fibres bridged larger cracks while polypropylene fibres controlled smaller cracks. HF-SCC2 was therefore the strongest mixture across the three reported mechanical tests.

#### Chloride penetration resistance

Chloride resistance improved substantially with hybrid fibre addition. SCC-C recorded a penetration depth of 18.5 mm and an RCPT charge of 2850 coulombs. HF-SCC2 recorded the minimum values of 10.8 mm and 1580 coulombs. HF-SCC3 remained better than the control but performed slightly below HF-SCC2, reinforcing the requirement for an optimum fibre dosage rather than the maximum dosage.

Table 11. Chloride penetration and RCPT results

| Mix ID  | Penetration depth (mm) | RCPT charge passed (coulombs) | Chloride resistance category (reported) |
|---------|------------------------|-------------------------------|-----------------------------------------|
| SCC-C   | 18.5                   | 2850                          | Moderate                                |
| HF-SCC1 | 14.2                   | 2150                          | Low                                     |
| HF-SCC2 | 10.8                   | 1580                          | Very Low                                |
| HF-SCC3 | 12.1                   | 1765                          | Low                                     |

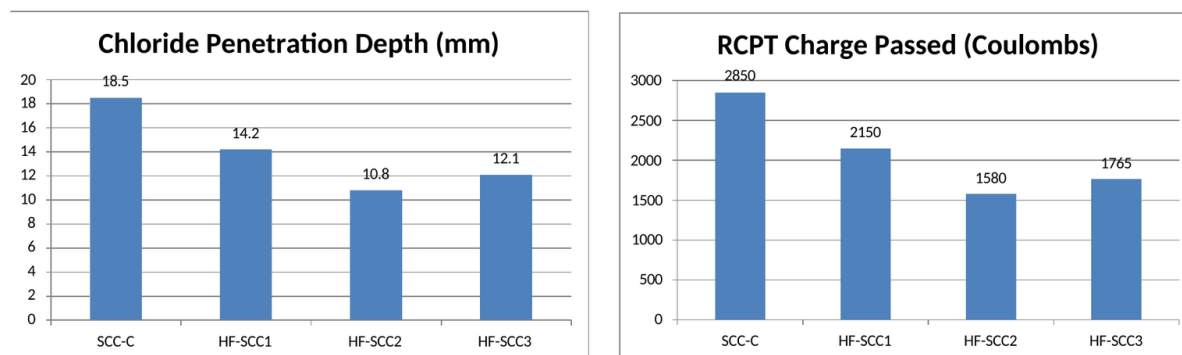


Fig. 7. Chloride penetration depth and RCPT charge passed for the four SCC mixtures.

Table 12. Reduction in chloride penetration and RCPT charge relative to SCC-C

| Mix ID  | Penetration-depth reduction (%) | RCPT reduction (%) |
|---------|---------------------------------|--------------------|
| HF-SCC1 | 23.24%                          | 24.56%             |
| HF-SCC2 | 41.62%                          | 44.56%             |
| HF-SCC3 | 34.59%                          | 38.07%             |

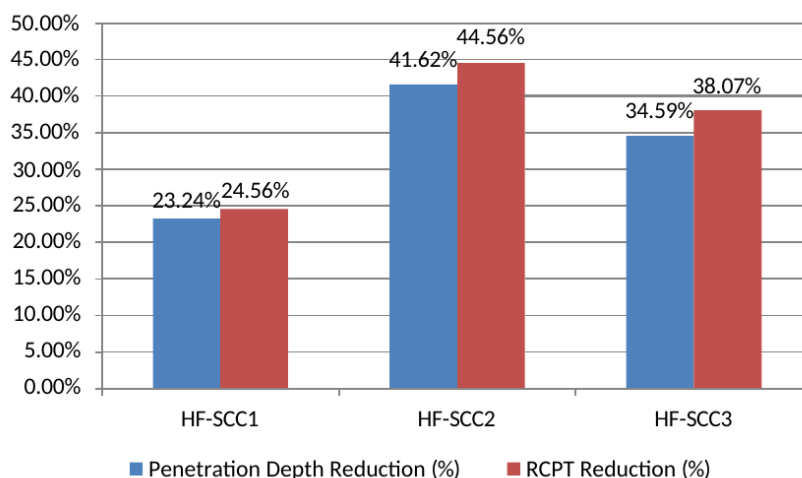


Fig. 8. Percentage reduction in chloride penetration depth and RCPT charge.

Relative to the control, HF-SCC2 reduced penetration depth by 41.62% and RCPT charge by 44.56%. The thesis attributes this improvement to the combined restriction of microcracks by polypropylene fibres and bridging of larger cracks by steel fibres, which reduced connected pathways for chloride transport.

### Overall performance

The complete dataset shows a trade-off between fresh flow and hardened durability. SCC-C provided the highest slump flow but the lowest strength and the highest chloride penetration. HF-SCC2 retained acceptable SCC fresh properties while producing the highest mechanical strengths and the lowest chloride-transport values. Table 13. Comparative performance summary

| Parameter                           | SCC-C | HF-SCC1 | HF-SCC2 | HF-SCC3 |
|-------------------------------------|-------|---------|---------|---------|
| Slump flow (mm)                     | 745   | 720     | 690     | 655     |
| 28-day compressive strength (MPa)   | 46.5  | 49.8    | 53.4    | 51.2    |
| 28-day split-tensile strength (MPa) | 3.85  | 4.42    | 4.96    | 4.78    |
| 28-day flexural strength (MPa)      | 5.20  | 6.05    | 6.78    | 6.51    |
| Chloride penetration (mm)           | 18.5  | 14.2    | 10.8    | 12.1    |

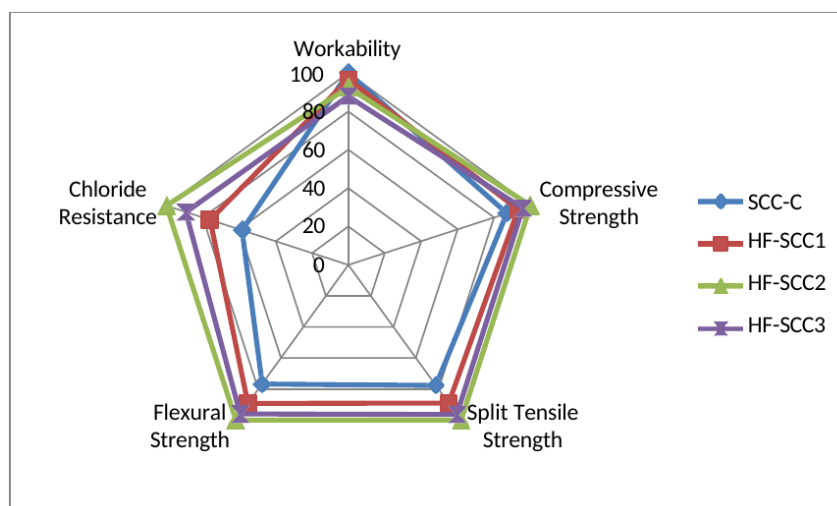


**Fig. 9. Overall performance comparison of conventional and hybrid fibre-reinforced SCC mixtures.**

HF-SCC2, containing 0.75% steel fibre and 0.15% polypropylene fibre, provided the best combined response. Increasing the dosage to HF-SCC3 reduced workability and produced lower mechanical and chloride-resistance performance than HF-SCC2. The optimum result therefore depended on balanced fibre content and adequate self-compaction.

## VI. CONCLUSION

The experimental investigation demonstrates that hybrid steel-polypropylene fibre reinforcement can improve the mechanical and chloride-resistance performance of self-compacting concrete when the dosage is controlled. The principal conclusions are:

- All four mixtures satisfied the fresh-property acceptance ranges reported in the thesis, confirming adequate self-compacting behaviour despite the reduction in flow caused by fibre addition.
- HF-SCC2 achieved the highest 28-day compressive, split-tensile, and flexural strengths of 53.4, 4.96, and 6.78 MPa.
- Compared with SCC-C, the HF-SCC2 mechanical improvements were 14.84% in compression, 28.83% in split tension, and 30.38% in flexure.
- HF-SCC2 recorded the lowest chloride penetration depth of 10.8 mm and the lowest RCPT charge of 1580 coulombs.
- The corresponding reductions relative to the control were 41.62% for penetration depth and 44.56% for RCPT charge.

- The lower performance of HF-SCC3 relative to HF-SCC2 confirms that excessive fibre content can impair workability and the resulting overall performance.
- HF-SCC2, with 0.75% steel fibre and 0.15% polypropylene fibre, was the optimum mixture in the present study.

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