Comparative Analysis of Chloride Penetration in Sustainable Quaternary Blended SCC with and Without Polypropylene Fiber Reinforcement

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Abstract: This study focuses on the development of an economical Self-Compacting Concrete (SCC) that maintains its characteristic ability to flow under its own weight, fully occupying formwork without the need for vibrational compaction. The research aims to reduce waste and carbon emissions associated with cement production by optimizing the use of supplementary materials. Specifically, the study explores the effects of varying concentrations of fly ash and ground granulated blast furnace slag (GGBS), the substitution of 10% of cement with silica fume, and the inclusion of 0.2% polypropylene fiber (PPF) on SCC properties. Eight concrete mixes were evaluated: four incorporating PPF and four without. The results provide insights into the performance and environmental benefits of these modified SCC formulations. Also the study investigates the chloride penetration characteristics of Sustainable Quaternary Blended Self-Compacting Concrete (QBSCC) with and without polypropylene fiber reinforcement. Various QBSCC mixes were formulated by replacing Ordinary Portland Cement (OPC) with combinations of supplementary cementitious materials (SCMs) including silica fume (SF), fly ash (FA), and ground granulated blast furnace slag (GGBS). The Rapid Chloride Penetration Test (RCPT) was conducted at 28 and 56 days to assess chloride ion permeability. Results indicate that QBSCC mixes incorporating SCMs exhibit significantly lower chloride permeability compared to the control mix (MIX-1) composed of 100% OPC. MIX-4, containing 50% OPC, 10% SF, 10% FA, and 30% GGBS, shows the most promising performance with the lowest passed charges, suggesting enhanced durability against chloride ion penetration. Addition of 0.2% polypropylene fibers further enhanced chloride resistance, especially in the mix with the highest resistance to chloride penetration. Overall, the study concluded that QBSCC formulations with optimized SCM content and polypropylene fiber reinforcement have superior durability and reduced chloride permeability, making them suitable for construction in aggressive environments where chloride exposure is a concern.

Keywords: *SSC, QBSCC, Silica fume, Fly ash, GGBS, Polypropylene fibers, Durability Assessment, RCPT.*

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I. INTRODUCTION

The field of material science technologies has seen rapid advancements, particularly in enhancing the strength and durability of concrete over the past three decades. Concrete has evolved from a simple mixture of cement, aggregates, and water into a highly engineered material with various components tailored to specific construction needs. The increasing use of concrete in complex architectural forms and structures with densely packed reinforcement has necessitated the production of concrete that offers excellent filling ability, structural performance, and durability. Recent research has focused on improving these critical properties, leading to the development of self-compacting concrete (SCC). SCC, defined as concrete that can fill formwork under its own weight without vibratory compaction, is highly flowable and resists segregation, making it ideal for structures with tight reinforcement and limited access. Originating in Japan due to concerns over concrete durability and declining skilled labor, SCC was first proposed by Professor Okamura in 1988 and has since become an important material in the construction industry. It offers significant benefits, including improved quality, environmental and health protections, and economic efficiency, despite its initial higher cost. SCC utilizes more cement, superplasticizers, and supplementary materials like fly ash and ground granulated blast furnace slag (GGBS) to enhance fluidity and durability while reducing labor costs

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and noise pollution. In contrast to conventional concrete, SCC's ability to flow easily without the need for vibration provides substantial advantages in construction efficiency and worker safety. The use of mineral admixtures, like fly ash and silica fume, and fibers, such as polypropylene, further enhances the mechanical properties, durability, and overall performance of SCC, making it a superior choice for modern construction projects.

Polypropylene fibers offer significant reinforcement benefits in Self-Compacting Concrete (SCC), contributing to enhanced durability and performance. Composed of a thermoplastic polymer with high tensile strength, these fibers effectively reduce plastic shrinkage cracking and drying shrinkage cracks in SCC. They act as micro-reinforcements, improving tensile strength and crack resistance while enhancing concrete durability by reducing permeability. Polypropylene fibers also enhance toughness and ductility by arresting crack propagation and improving post-crack behavior, making them ideal for corrosive environments due to their corrosion resistance. However, challenges include the potential for improper mixing leading to fiber clumping, which can reduce their effectiveness in crack control. Additionally, visible fibers may not be aesthetically pleasing in some applications, although finer or color-matched fibers can mitigate this issue. Careful mix design adjustments are necessary as fiber addition can slightly affect concrete workability and setting time. The project aims to assess how polypropylene fibers enhance concrete's resistance to chloride ingress and impact its mechanical properties like compressive, tensile, and flexural strength. This comparative study focuses on sustainable quaternary blended Self-Compacting Concrete (SCC) with and without fiber reinforcement, aiming to optimize mix designs for chloride-rich environments while considering sustainability. The investigation's objectives include designing SCC mixes with varying percentages of Fly ash, GGBFS, Silica fume, and 0.2% polypropylene fibers, evaluating their fresh and hardened properties, and assessing the durability through tests like the Rapid Chloride Penetration Test (RCPT). The study was conducted in phases: procurement of SCC materials, laboratory testing and mix design refinement, casting and curing of specimens, mechanical property testing at 28 and 56 days, and evaluation of durability properties against sulfuric acid attacks. The final phase involved analyzing experimental data to draw conclusions about the efficacy and performance of SCC with and without polypropylene fiber reinforcement. Overall, understanding the benefits and limitations of incorporating fibers into concrete is crucial for optimizing construction practices and ensuring long-term durability against environmental stressors like chloride ion penetration, as assessed through tests such as the Rapid Chloride Penetration Test (RCPT).

II. MATERIALS

A. Cement

In the current investigation, ordinary Portland cement (OPC) of grade 43, Ramco brand, adhering to IS: 269-2015 standards have been used. The assessment of the cement includes testing for specific gravity, normal consistency, setting time and compliance with the relevant Indian Standard Code of Practice IS:4031-1988.

Table 1 Physical properties of cement

Sl. No.	Properties	Results
1	Specific Gravity	3.06
2	Fineness modulus	5 %
3	Normal Consistency	31 %
4	Initial Setting Time	160 min
5	Final Setting Time	Min

B. Fine Aggregate

The Fine aggregates were sieved in accordance with IS: 2386 (Part I) – 1963, and the material was tested in accordance with the Indian standard code of practice. The results were found to satisfy the relevant Indian standard specification for aggregates for concrete specific gravity, density, voids, absorption, and bulking (IS: 2386 (Part III) – 1963). The physical properties of fine aggregates are listed below.

Table 2 Properties of Fine Aggregate

Sl. No.	Property	Result
1	Specific Gravity	2.65
2	Bulk density- compacted	1553 kg/m^3
3	Zone of aggregate	Zone II
4	Fineness modulus	3.28 %

C. Coarse Aggregate

The coarse aggregate is used at maximum fraction of 20 mm and 12.5 mm. According to IS 383-1970 & IS 2386-1983, experimental research was conducted to determine the characteristics of coarse aggregate, which are shown in Table 3.

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Table 3 Properties of Coarse Aggregate

Sl. No.	Properties	Results
1	Specific Gravity	2.62
2	Bulk density-compacted	1565 kg/m^3
3	Fineness modulus	%

D. Water

Water in concrete serves as a crucial component, initiating the hydration process in cement and enabling the binding of other materials. The quality and quantity of water have a direct impact on the concrete; therefore, it must not contain any harmful material.

E. Silica fume

Silica fume, also known as micro silica, is an artificial pozzolanic admixture made from high-purity quartz reduced with coal in an electric arc furnace. It consists of nano crystalline silicon dioxide particles, smaller than 1 micron, and is processed to remove impurities and control particle size. The silica fume used in this study has a specific gravity of 2.12, a grey color, a specific surface area of 22 m²/g, and activity indices of 107% at 7 days and 110% at 28 days.

F. Fly Ash

Fly ash, a fine particulate by-product of coal combustion in thermal power plants, is widely used as a pozzolan and comes in two classes based on coal type. This study uses fly ash from an RMC plant conforming to IS: 3812:2003, with a specific gravity of 2.15, a fineness specific surface of 400 min, and 23% passing through a 45-micron sieve.

G. GGBS

Ground granulated blast furnace slag (GGBS), a byproduct of iron production, enhances concrete's workability, strength, and durability by incorporating CaO, SiO_2, Al_2O_3, and MgO, dried and ground into fine particles. In this study, GGBS from an RMC plant, with a specific gravity of 2.91, dull white color, fineness of 342 m²/kg, and activity indices of 70.91% at 7 days and 96.7% at 28 days, is utilized.

H. Superplasticizers

In this study, Glenium SKY 8233 from BASF Construction Chemicals (India) Pvt. Ltd. is employed as a superplasticizer for producing self-compacting concrete. It is a polycarboxylic ether-based viscous liquid with a reddish-brown color, density of 1.1 kg/liter, pH of 6.6, chloride content below 0.1%, and alkaline content below 3%. The dosage of this superplasticizer was determined using a Marsh cone test to optimize flow time and ensure compatibility with the concrete mix.

I. Polypropylene Fibers

RECRON-3S polypropylene fibers with a length of 12 mm and diameter ranging from 0.025 to 0.04 mm are investigated as reinforcement in self-compacting concrete (SCC). These fibers, characterized by a specific gravity of 0.90-0.91, a melting point between 160-165 °C, excellent alkali stability, and an aspect ratio of 300-480, aim to enhance SCC's toughness, durability, workability, and resistance to shrinkage and corrosion.

III. MIX DESIGN

The study evaluates various formulations of self-compacting concrete (SCC), including mixes with different percentages of cement replaced by silica fume, fly ash, and ground granulated blast furnace slag (GGBS). Additionally, polypropylene fibers are incorporated into select mixes to assess their impact on concrete properties. These formulations are designed to enhance the performance and sustainability of SCC, with detailed compositions provided for each mix variant. Eight types of mix proportions were used, four mix incorporating 0.2% polypropylene fibers and rest excluding fibers. The self-compacting concrete (SCC) mix with and without fibers was formulated without any cement replacement, designated as Mix 1 and Mix 1PPF. Subsequently, cement was replaced with 10% silica fume, 30% FA, and 10% GGBS, labeled as Mix 2 and Mix 2PPF with and without fibers. Analogously, the cement replacements of 10% silica fume, 20% FA, and 20% GGBS, termed Mix 3 and Mix 3PPF for with and without fibers, respectively, were utilized in the third mix. Finally, the fourth mix substituted cement with 10% silica fume, 10% FA, and 30% GGBS, which was identified as Mix 4 and Mix 4PPF with and without fibers, respectively. The concrete mix code for samples with PPF indicates the addition of polypropylene fiber.

IV. PREPARATION OF CONCRETE SPECIMENS AND TESTING METHODS

The concrete mixture was created in a pan mixer. The coarse and fine aggregates were first thoroughly blended, then cement and supplementary cementitious materials were added and mixed well to achieve a consistent colour. In the designs containing PP fibers, fibers are added, to the mix and mixed for 2 min. Subsequently, 60% water was added and the remaining water was mixed with super plasticizer and then added to the pan mix. After the mixing process was complete, necessary tests – Slump Flow, T500, J-ring V-Funnel, L-Box and U-Box – Test were conducted to determine the flow properties of the fresh QBSCC. The results of these tests are compared with the EFNARC requirements for SCCs. since it is a self-compaction concrete, the concrete flows under its own weight, so the moulds are not vibrated. After the concrete is demoulded, it is transferred to a curing tank. Then specimens are cured in water for 7, 28, and 56 days. Compressive, split tensile, and flexural strength tests are performed based, on the IS 516, requirements, the specimens were prepared to determine the strength of concrete. The durability properties of concrete were determined at 28days and 56 days. After the samples were cured for 7 ,28 and 56-day, cubes of size 150× 150 ×150 mm samples were tested for

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compressive strength and 150mm diameter 300 mm length cylindrical samples underwent tensile strength tests respectively, based on the IS 516. The flexural strength was calculated using, 100 × 100 × 500 mm beams. The experimental phase assessed the chloride penetration resistance of concrete using rapid chloride penetration tests (RCPT) as per ASTM C1202 standards. Concrete cylinders of 100 mm diameter Samples with a depth of 50±3 mm were cast and cured for 28 and 56 days, then samples were cut, epoxy-coated, and tested. Testing cells were filled with NaCl and sodium hydroxide solution, and a 60V current was applied for six hours. The charge passed through each specimen was measured in coulombs using a trapezoidal rule formula. The following formula, based on the trapezoidal rule can be used to calculate the average current flowing through one cell.

$$Q = 900(I_0+2I_{30}+2I_{60}+2I_{90}+2I_{120}+\ldots+2I_{300}+2I_{330}+I_{360})$$

Where, Q = current flowing through one cell (coulombs)

I_0 = Current reading in amperes immediately after voltage is applied, and

I_t = Current reading in amperes at t minutes after voltage is applied.

Based on ASTM C1202, chloride penetrability is categorized into five levels: high (>4000 C), moderate (2000-4000 C), low (1000-2000 C), very low (100-1000 C), and negligible (<100 C).

Fig 1 Cut and epoxy coated specimens before testing

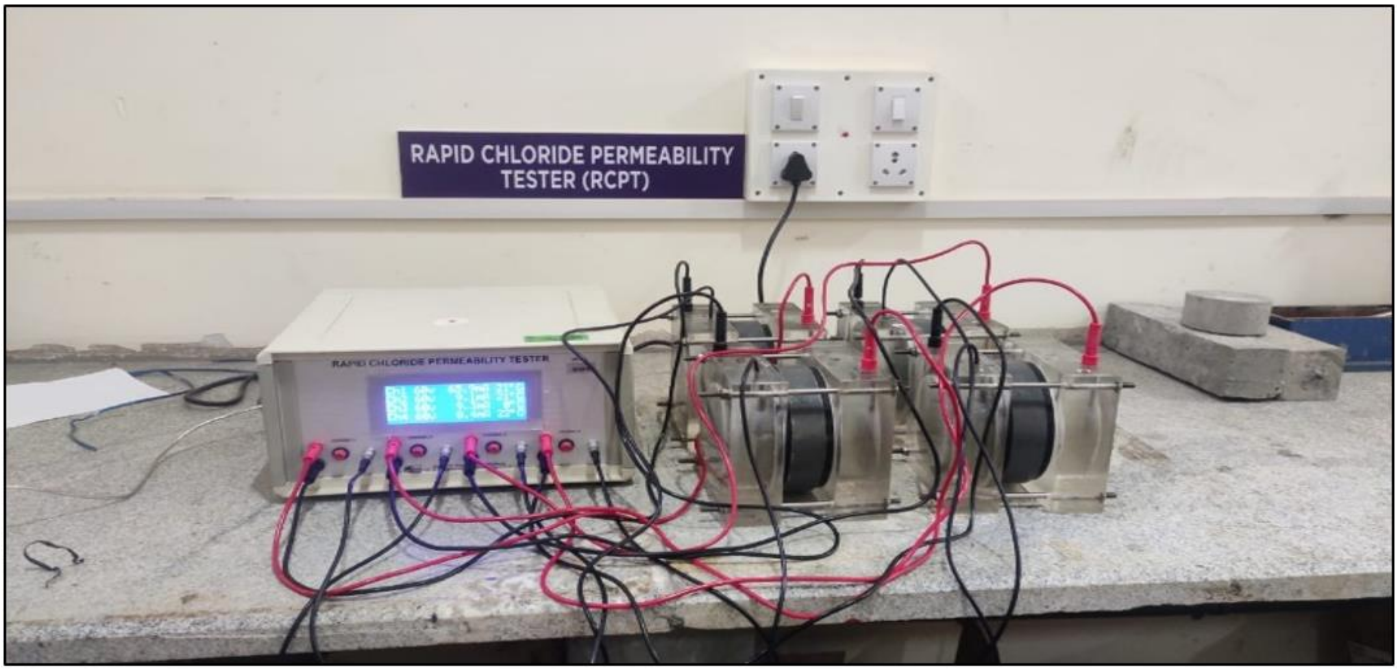

Fig 2 Rapid chloride penetration test setup

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V. DISCUSSIONS OF TEST RESULTS

A. Fresh Properties of Blended Self-Compacting Concrete

The test results for Quaternary Blended Self-Compacting Concrete (QBSCC), with and without fibers, reveal significant variations in key parameters across Mix-1 to Mix-4 and Mix-1PPF to Mix-4PPF. These parameters include slump flow, T500 time, V-funnel time, L-box ratio, U-box, and J-ring slump.

➢ *Slump Flow Test Results:*

The comparison of slump flow results for various concrete mixes with and without polypropylene fibers (PPF) highlights the impact of fiber addition on the workability of self-compacting concrete (SCC). MIX-1 showed a slump flow of 650 mm without fibers, which decreased by 9.23% to 590 mm with 0.2% PPF. MIX-2's slump flow dropped from 690 mm to 675 mm (2.17% reduction), while MIX-3 experienced a decline from 680 mm to 640 mm, reflecting a 5.88% decrease. Lastly, MIX-4 saw an 8.15% reduction from 675 mm to 620 mm upon the addition of PPF. Overall, these results indicate that incorporating polypropylene fibers tends to reduce the slump flow of SCC, attributed to the fibers' water absorption and increased internal friction, which diminishes flowability.

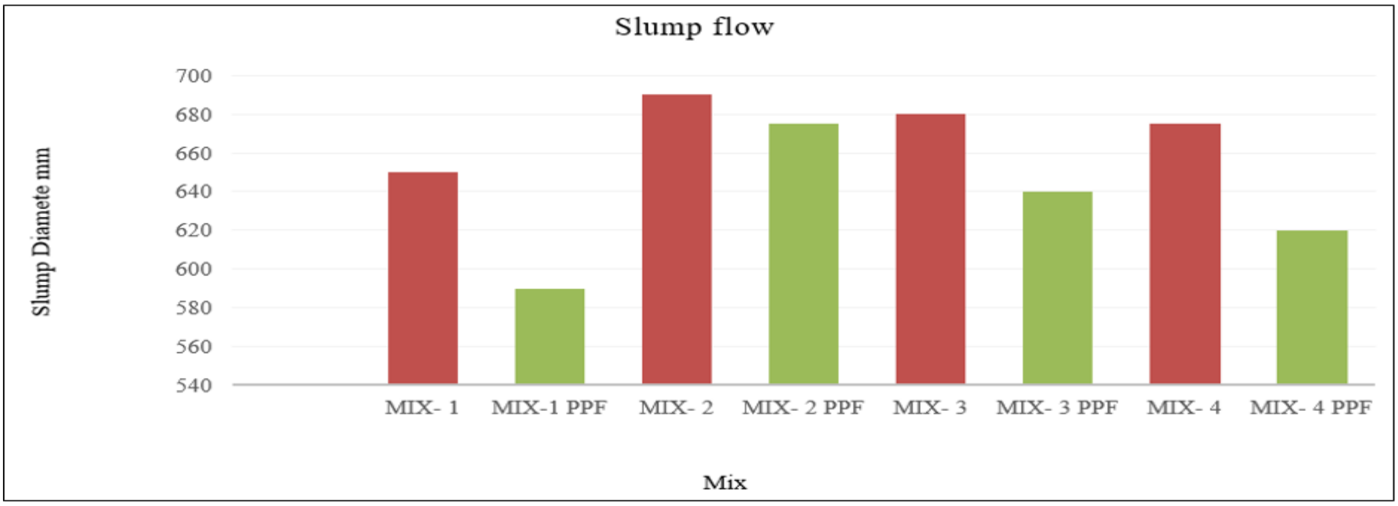

Fig 3 Variation of Slump flow

➢ *T500 mm Slump Flow Time Test:*

The T500 time is a critical measure for assessing the flow rate of self-compacting concrete (SCC) and is essential for determining its performance based on EFNARC 2005 guidelines. In this study, MIX-1, composed of 100% ordinary Portland cement (OPC), recorded a T500 time of 4.6 seconds, indicating suitability for scarcely reinforced structures; however, the addition of polypropylene fibers (PPF) raised this to 6.26 seconds, reflecting increased flow resistance. MIX-2, with 50% OPC, 10% silica fume (SF), 30% fly ash (FA), and 10% ground granulated blast furnace slag (GGBS), showed a T500 time of 3.1 seconds, increasing to 3.48 seconds with PPF. Similarly, MIX-3 and MIX-4 displayed T500 times of 3.8 and 4 seconds, respectively, which rose to 4.63 and 5.1 seconds upon adding PPF, indicating a consistent trend of reduced flowability. All mixes, with and without PPF, remained classified under SF1 or SF2 categories, suitable for various structural applications. The findings highlight the trade-off between enhanced durability and decreased workability due to PPF addition, necessitating careful mix design considerations.

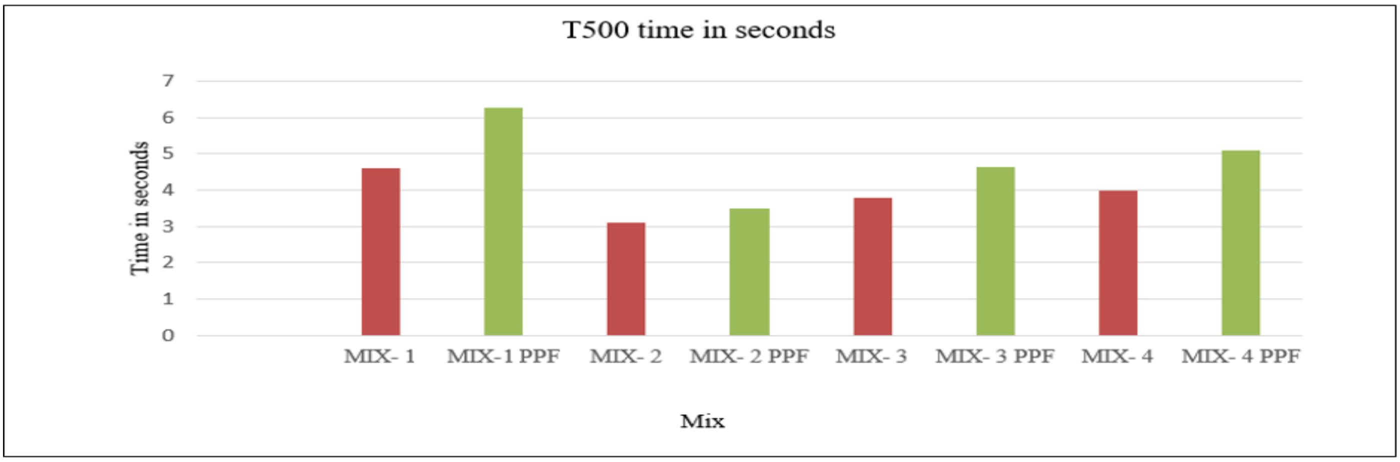

Fig 4 Variations of T500 mm Slump Flow Time Test

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➤ *J-Ring Test:*

The comparison of concrete mixtures based on J-ring slump and height reveals significant differences in workability and stability. MIX-2 exhibits the highest J-ring slump of 675 mm and the lowest height of 5 mm, indicating superior workability and stability. In contrast, MIX-1 PPF shows the lowest slump at 530 mm and the highest height at 14 mm, implying reduced workability and potential stability issues.MIX-3 PPF presents moderate characteristics with a slump of 610 mm and height of 10 mm. Overall, MIX-2 is the most suitable choice for construction due to its optimal combination of high slump and low height, ensuring durability and structural integrity.

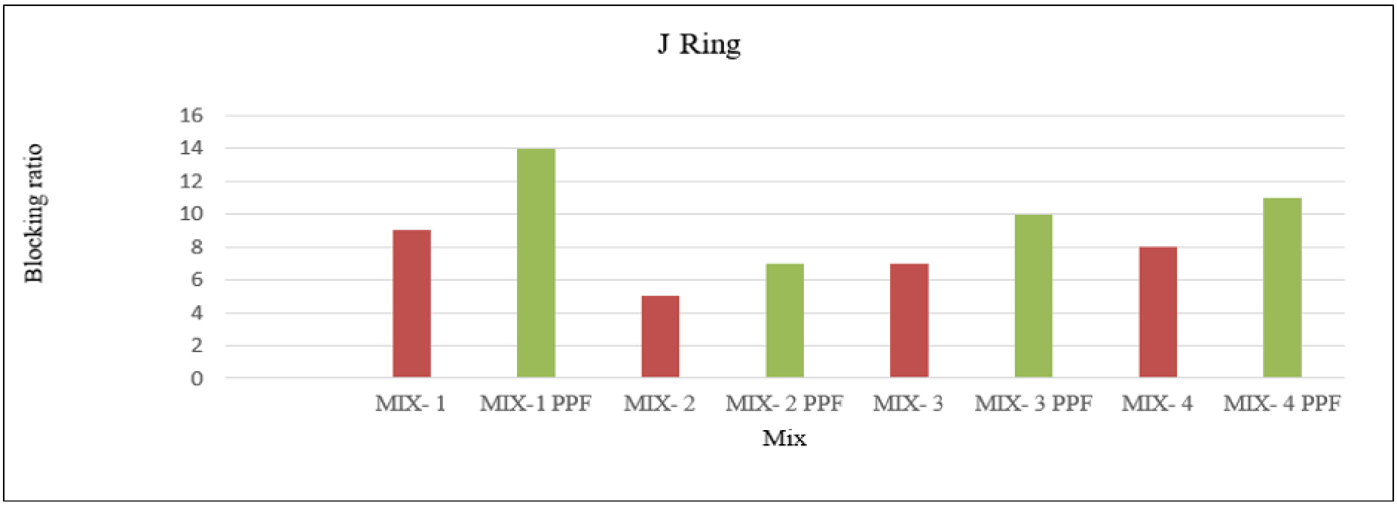

Fig 5 Variations of J-Ring Test Results

➤ *U Box Test:*

The U-box test results reveal notable differences among the concrete mixtures. MIX-2 shows the lowest U-box value at 8 mm, indicating excellent segregation resistance and stability. Conversely, MIX-1 PPF has the highest U-box value of 27 mm, suggesting poor segregation resistance and potential stability issues. MIX-3 PPF presents a moderate value of 16 mm, while MIX-2 PPF has a promising value of 11 mm, both indicating moderate segregation resistance. MIX-4 PPF falls in between with a U-box value of 19 mm. Overall, MIX-2 is identified as the most suitable option for construction due to its superior segregation resistance and stability, essential for uniformity and durability in concrete structures.

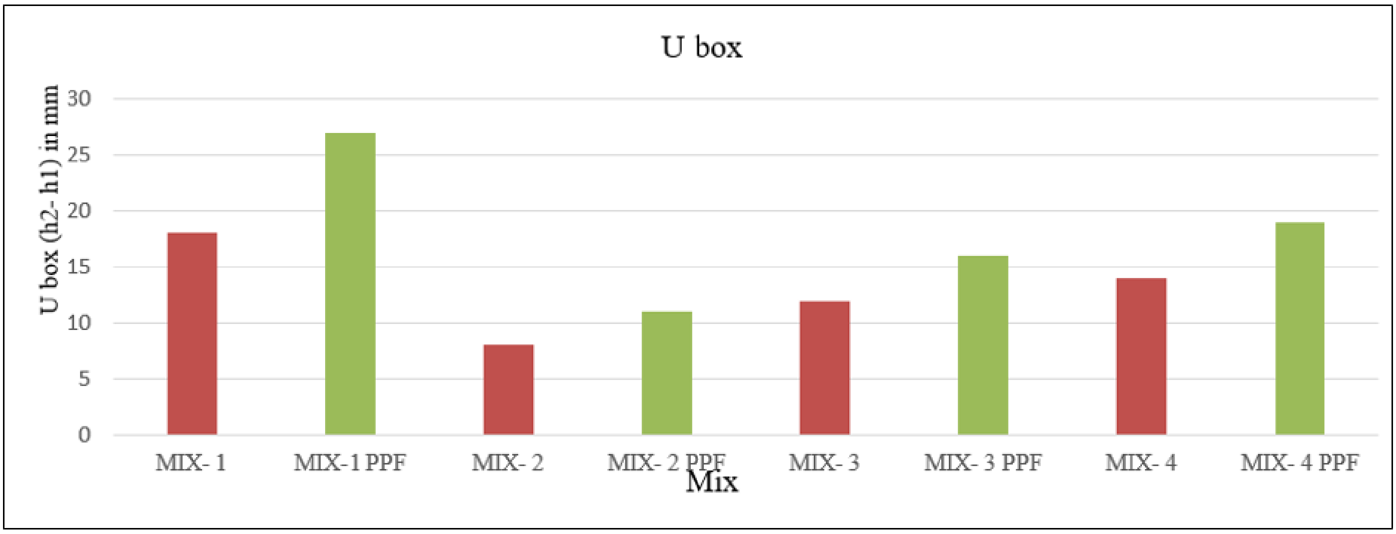

Fig 6 Variations of U-box test result

➤ V-Funnel Test:

The V funnel time results provide crucial insights into the flowability of the different concrete mixtures. Among these, MIX-2 demonstrates the shortest V funnel time at 6.8 seconds, indicating excellent flowability and ease of placement. MIX-2 PPF also shows promising characteristics with a V funnel time of 7.89 seconds, suggesting good flowability. MIX-3 and MIX-3 PPF offer moderate flowability with V funnel times of 7.6 and 9.25 seconds, respectively. MIX-1, MIX-4, MIX-1 PPF, and MIX-4 PPF exhibit relatively longer V funnel times, indicating lesser flowability compared to the others. Considering construction requirements that prioritize ease of placement and good flowability, MIX-2 and MIX-2 PPF emerge as the most suitable options. Their optimal combination of materials results in superior flowability, which is essential for efficient and effective construction processes.

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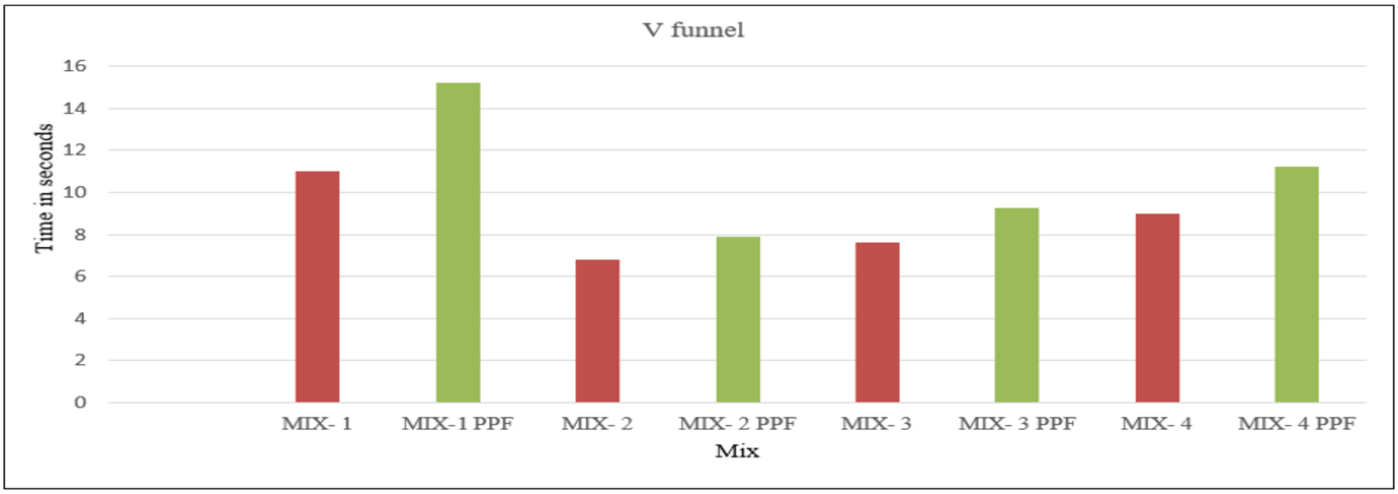

Fig 7 Variations of V funnel results

➢ *L-box test:*

The L-box ratio results highlight differences in flowability and segregation resistance among the concrete mixtures. MIX-1 PPF shows the lowest L-box ratio of 0.77, indicating excellent flowability and minimal segregation risk. MIX-2 and MIX-3 PPF have L-box ratios of 0.91 and 0.87, respectively, also suggesting favorable flowability. MIX-2 PPF and MIX-3 exhibit slightly lower ratios of 0.93 and 0.90, respectively. MIX-4 PPF and MIX-4 have ratios of 0.83 and 0.87, indicating relatively lower flowability but potentially higher segregation resistance. Given the construction requirements for optimal flowability and segregation resistance, MIX-1 PPF is the most suitable choice, ensuring uniformity and durability in concrete structures.

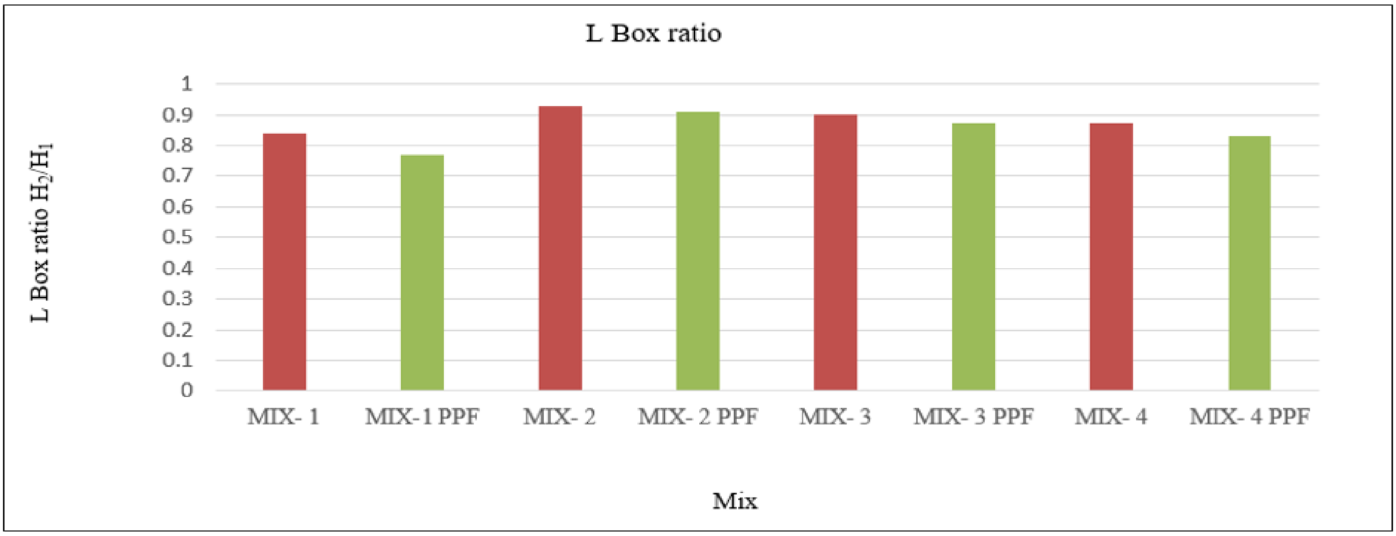

Fig 8 L Box ratio of QBSCC

The summary of results from the various concrete mixtures presents a range of characteristics relevant to construction applications. MIX-2, comprising 50% OPC, 10% SF, 30% FA, and 10% GGBS, emerges as particularly suitable for construction purposes. It displays a high slump flow of 690 mm, signifying excellent workability, and a short T500 time of 3.1 seconds, indicating rapid setting properties. Furthermore, MIX-2 demonstrates the shortest V funnel time at 6.8 seconds and a relatively low L box ratio of 0.93, suggesting good flowability and minimal segregation potential. Additionally, MIX-2 exhibits a low U box value of 8 mm and a low J-ring slump of 5 mm, indicating good stability and resistance to segregation. Overall, MIX-2 stands out as the most balanced and effective option for constructing durable and high-quality concrete structures.

B. Strength Properties of Self-Compacting Concrete

➢ *Compressive Strength Test:*

The compressive strength results reveal significant improvements in concrete mixes with polypropylene fibers (PPF) compared to those without. For Mix-1, strengths increase from 30.17 MPa at 7 days to 44.12 MPa at 56 days, while Mix-1 PPF shows higher values of 31.56 MPa and 47.34 MPa, respectively. Similarly, Mix-2 exhibits a rise from 27.41 MPa to 46.34 MPa, with Mix-2 PPF showing enhanced strengths. Mix-3 without fibers reaches 30.77 MPa at 7 days, compared to 33.30 MPa for Mix-3 PPF at the same age. Mix-4 shows compressive strengths of 30.87 MPa without fibers and 34.17 MPa with fibers at 7 days. Overall, the addition of PPF consistently improves compressive strength across all mixes, enhancing durability and making

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these fiber-reinforced mixes suitable for construction. The increase in strength is attributed to the interlocking mechanisms of the fibers and aggregates, which mitigate crack propagation. Among the variants, Mix-4 PPF (50% OPC + 10% SF + 10% FA + 30% GGBS + 0.2% PPF) performs best at all time intervals. The combination of fly ash (FA), ground granulated blast-furnace slag (GGBS), and silica fume (SF) contributes to higher compressive strength due to their synergistic effects, enhancing the concrete's packing density and microstructure.

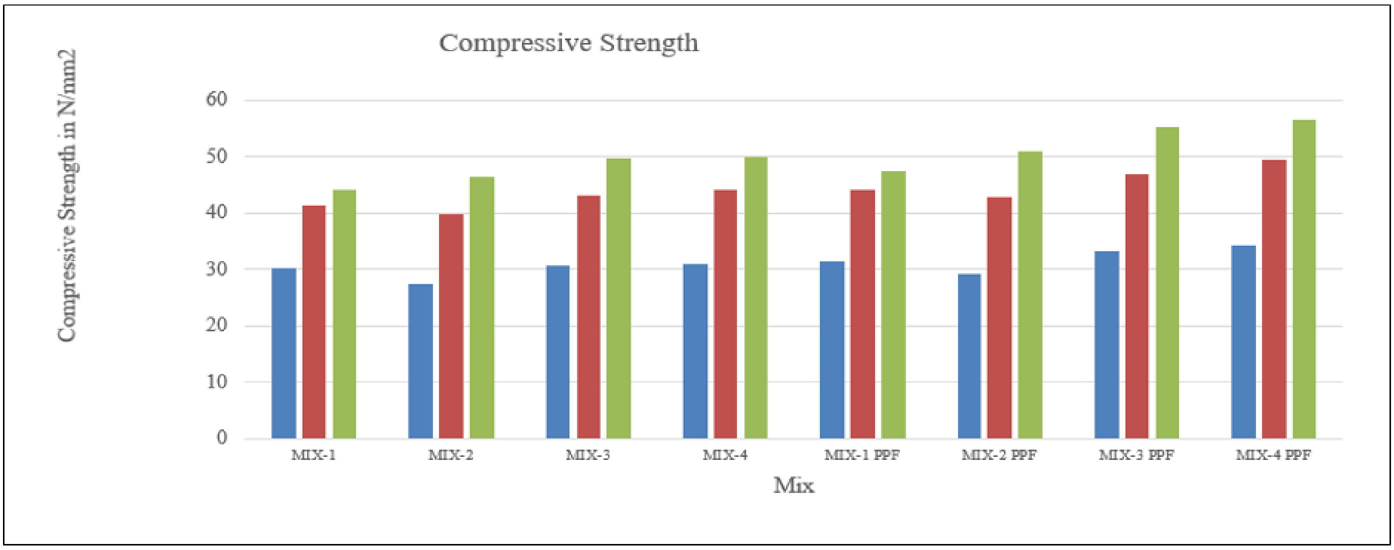

Fig 9 Variation of Compressive Strength with different curing stage

➢ *Split Tensile Strength:*

The split tensile strength results for various concrete mixes, with and without polypropylene fibers (PPF), exhibit significant variations over time. For Mix-1 without fibers, strengths are 2.37 MPa at 7 days, 3.08 MPa at 28 days, and 3.35 MPa at 56 days. In comparison, Mix-1 PPF shows higher values of 2.55 MPa (7.6% increase), 3.38 MPa (9.7% increase), and 3.62 MPa (8.1% increase). Similarly, Mix-2 exhibits strengths of 2.07 MPa, 2.95 MPa, and 3.40 MPa, while Mix-2 PPF shows increases to 2.31 MPa (11.6%), 3.32 MPa (12.5%), and 3.90 MPa (14.7%). Mix-3 strengths are 2.43 MPa, 3.12 MPa, and 3.71 MPa, with Mix-3 PPF achieving 2.75 MPa (13.2%), 3.67 MPa (17.6%), and 4.30 MPa (15.9%). Mix-4 results are 2.62 MPa, 3.35 MPa, and 4.00 MPa, while Mix-4 PPF reaches 3.02 MPa (15.3%), 4.01 MPa (19.7%), and 4.81 MPa (20.3%). These strength improvements are attributed to the PPF's role in inhibiting microcrack growth through its bridging effects. Quaternary Blended Self-Consolidating Concrete (QBSCC) mixes, especially QBSCC Mix 4, demonstrate superior split tensile strength compared to conventional mixtures, enhanced by the use of supplementary cementitious materials (SCM) that promote denser concrete and late pozzolanic reactions.

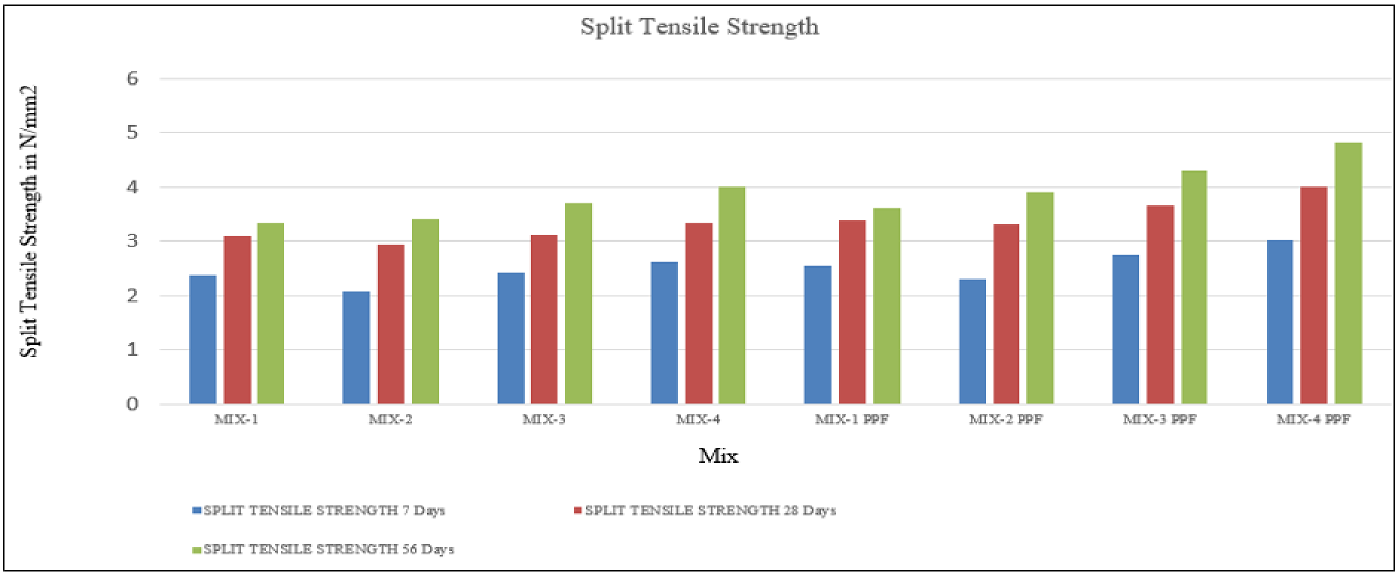

Fig 10 Variation of Split Tensile Strength with different curing stage

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➢ *Flexural Strength:*

The flexural strength results for self-compacting concrete (SCC) at 7, 28, and 56 days are illustrated graphically. QBSCC mixes with supplementary cementitious materials (SCM) show flexural strengths ranging from 4.19 MPa to 4.86 MPa at 7 days, 6.02 MPa to 6.15 MPa at 28 days, and 6.19 MPa to 6.73 MPa at 56 days. In contrast, mixes with SCM and 0.2% polypropylene fibers (PPF) display enhanced strengths of 4.47 MPa to 5.53 MPa at 7 days, 6.60 MPa to 7.20 MPa at 28 days, and 6.73 MPa to 7.90 MPa at 56 days. Notably, Mix-3 and Mix-4 outperform conventional Mix-1, achieving increases of 12.77% and 16% at 7 days, and 4.85% and 8.87% at 56 days, respectively. The incorporation of PPF in Mix-1 results in flexural strength enhancements of 6.59%, 9.63%, and 8.78% at 7, 28, and 56 days. Overall, the addition of SCM and PPF significantly boosts the flexural strength of QBSCC mixes due to improved mechanical bonding and crack resistance.

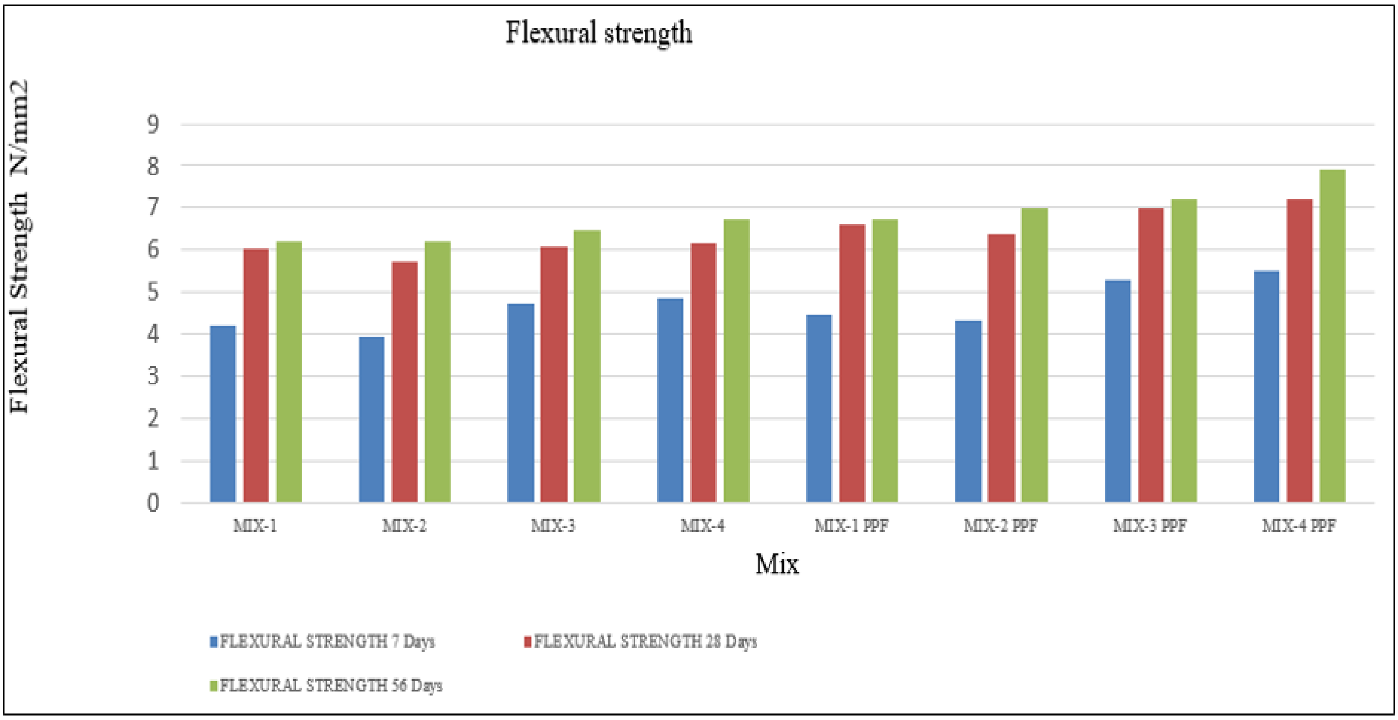

Fig 11 Variation of Flexural Strength with different curing stage

C. Durability Properties of Self-Compacting Concrete on Rapid Chloride Penetration Test

Table 4 Passed Charges (Coulomb)

Passed Charges (Coulomb)						
	28 Days			56 Days		
MIX	**Specimen 1**	**Specimen 2**	**Average**	**Specimen 1**	**Specimen 2**	**Average**
Mix-1	937.17	1103.76	1020.46	847.8	835.56	841.68
Mix-2	398.55	438.99	418.77	362.7	284.94	323.82
Mix-3	329.9	355.72	342.81	315.54	299.07	307.305
Mix-4	310.2	312.6	311.4	290.65	278.96	284.805
Mix-1 PPF	918.2	956.14	937.17	908.45	894.97	901.71
Mix-2 PPF	326.18	365.2	345.69	245.85	200.19	223.02
Mix-3 PPF	269.52	277.86	273.69	210.65	202.45	206.55
Mix-4 PPF	265.34	276.46	270.9	205.98	190.74	198.36

➢ *RCPT values of QBSCC Mixes without fibres*

The Rapid Chloride Permeability Test (RCPT) results show that replacing Ordinary Portland Cement (OPC) with supplementary cementitious materials (SCMs) significantly improves concrete durability. MIX-1 (100% OPC) recorded 1020.46 Coulombs at 28 days and 841.68 at 56 days, classified as "Low" permeability. MIX-2 (50% OPC, 10% Silica Fume, 30% Fly Ash, 10% GGBS) reduced charges by 58.95% at 28 days and 61.54% at 56 days, achieving "Very Low" permeability. MIX-3 and MIX-4 further lowered permeability, with MIX-4 showing the greatest reduction—69.47% at 28 days and 66.17% at 56 days. MIX-4's high SCM content, especially GGBS, results in the lowest chloride ion penetration, making it the most durable and ideal for harsh environments like marine or deicing salt exposure. These results confirm that using SCMs significantly enhances concrete's resistance to chloride ingress and extends its service life.

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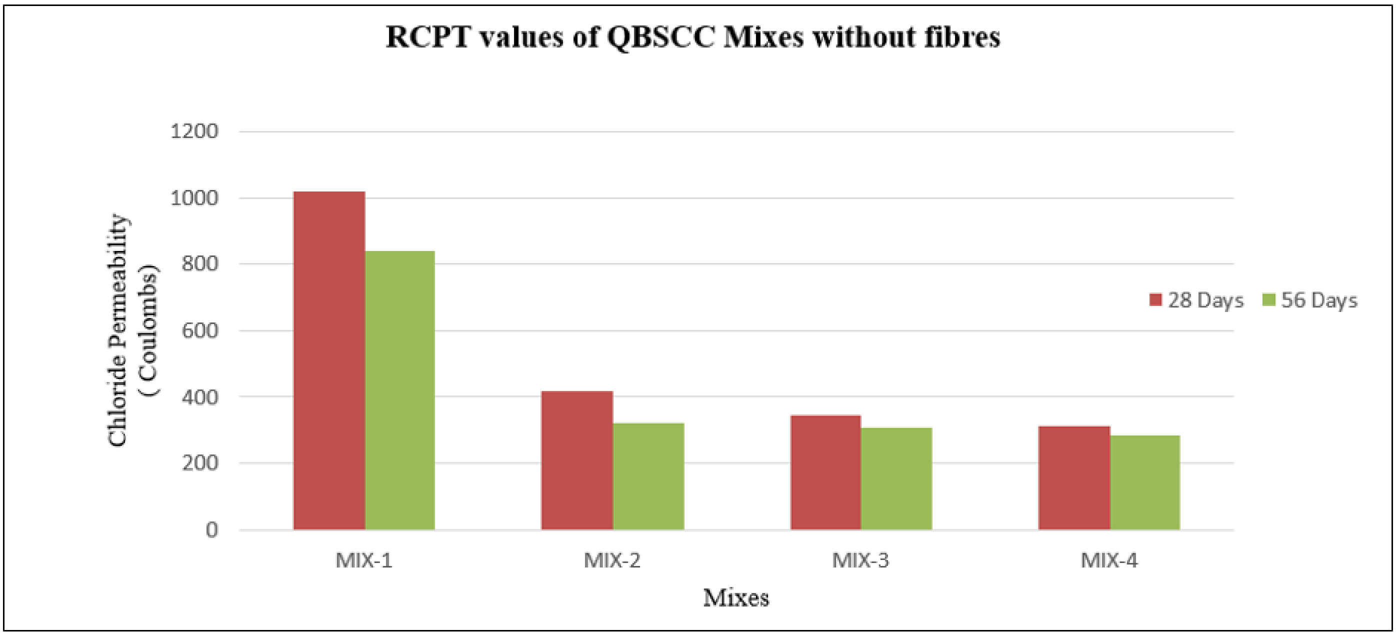

Fig 12 RCPT Results of QBSCC Mixes without fibers

➢ *RCPT values of QBSCC Mixes with fibres*

The Rapid Chloride Permeability Test (RCPT) results compare different mix proportions for their resistance to chloride ion penetration. MIX-1 PPF, composed of 100% OPC and 0.2% PPF, shows the highest permeability among the mixes, with charges of 937.17 Coulombs at 28 days and 901.71 Coulombs at 56 days. MIX-2 PPF, with a blend of OPC, SF, FA, GGBS, and 0.2% PPF, performs significantly better, with charges of 345.69 and 223.02 Coulombs at 28 and 56 days. MIX-3 PPF, using a different blend, shows further reduced permeability, with charges of 273.69 and 206.55 Coulombs. MIX-4 PPF demonstrates the lowest permeability, with charges of 270.9 and 198.36 Coulombs, indicating the highest resistance to chloride ion penetration. Overall, MIX-4 PPF offers the best durability for chloride exposure environments.

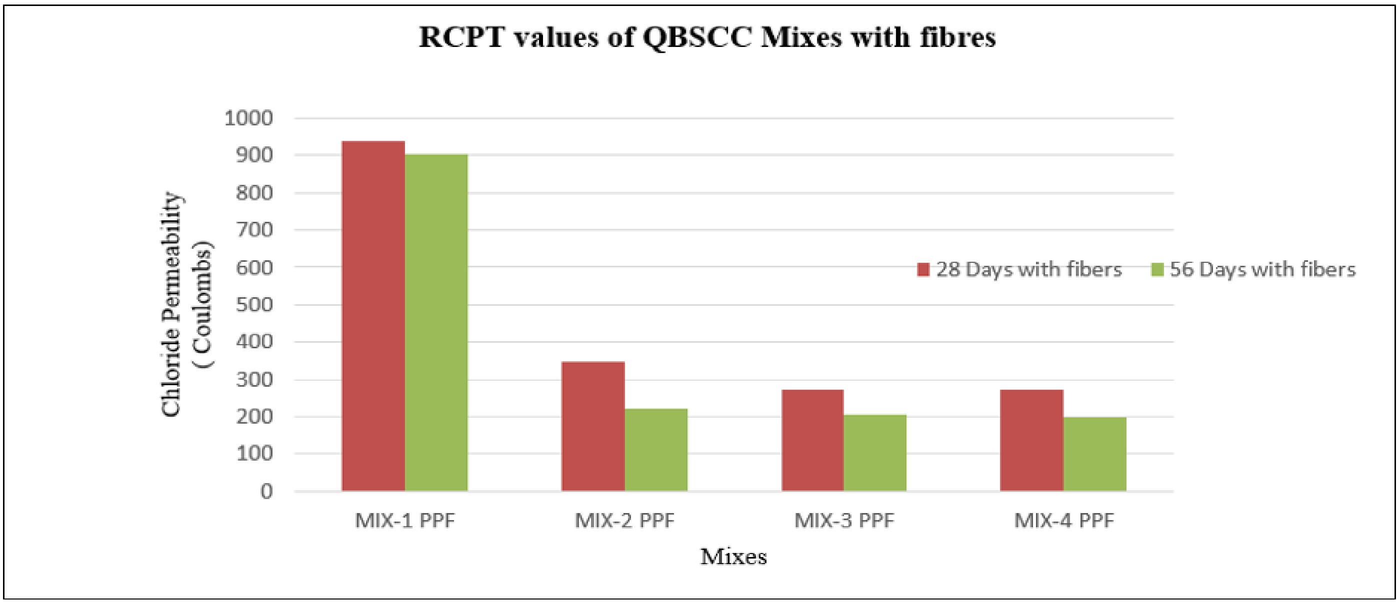

Fig 13 RCPT Results of QBSCC Mixes with fibers

➢ *Change in Permeability after 28 days curing for with and without fiber mixes*

The Rapid Chloride Permeability Test (RCPT) was conducted to compare the performance of concrete mixes with and without polypropylene fibers (PPF) at 28 days. MIX-1, made of 100% ordinary Portland cement (OPC), served as the baseline with an average passed charge of 1020.46 Coulombs, classified as "Low." Adding 0.2% PPF to MIX-1 reduced the charge to 937.17 Coulombs, classified as "Very Low," representing an 8.16% improvement in permeability. MIX-2, with 50% OPC and other supplementary materials, showed better performance with an average charge of 345.69 Coulombs after adding fibers, a 17.45% reduction. MIX-3, with similar materials, further reduced the charge by 20.16% after adding PPF. MIX-4, with the lowest baseline charge, saw a 12.99% reduction

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with PPF addition, resulting in the best overall performance at 270.9 Coulombs. The inclusion of PPF improves the durability and chloride resistance of all mixes, with MIX-4 PPF emerging as the most suitable for construction in aggressive environments.

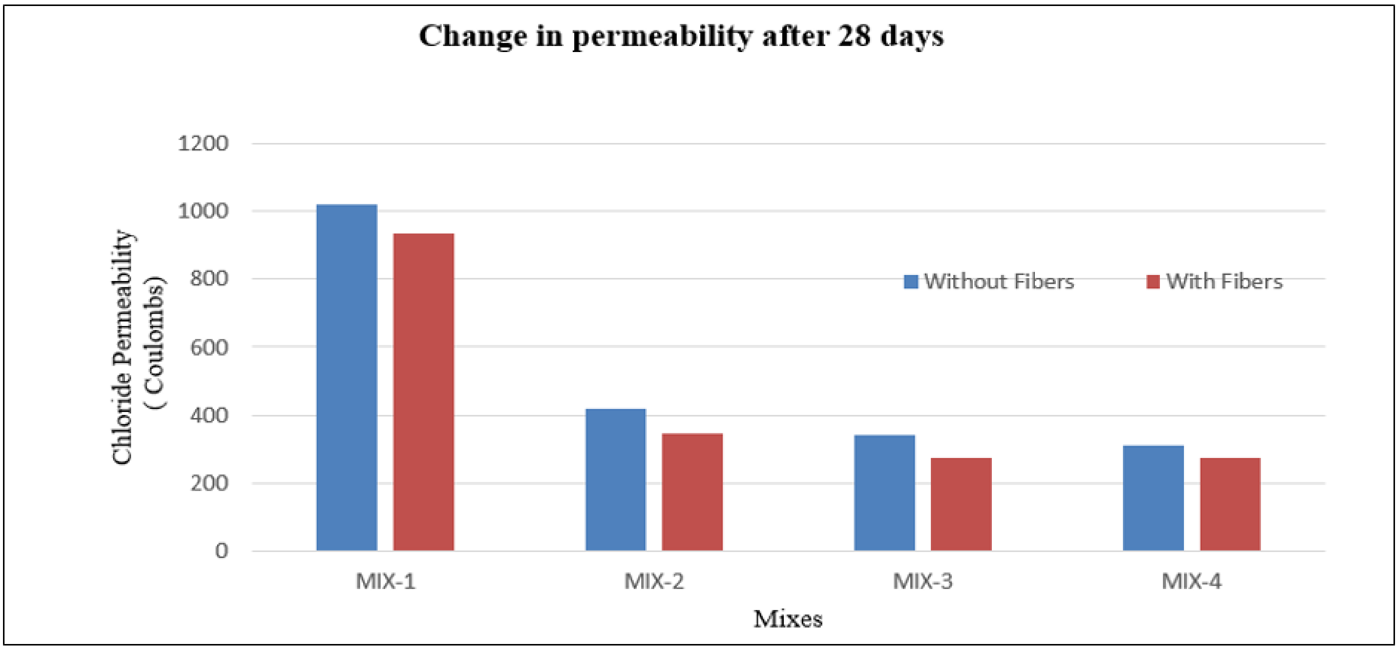

Fig 14 Variations in permeability after 28 days curing for with and without fiber mixes

➢ *Change in Permeability after 56 days curing for with and without fiber mixes*

The Rapid Chloride Permeability Test (RCPT) at 56 days was used to compare concrete mixes with and without polypropylene fibers (PPF) based on their passed charges in Coulombs. MIX-1, made of 100% OPC, had a charge of 841.68 Coulombs, classified as "Low," while adding 0.2% PPF (MIX-1 PPF) slightly increased it to 901.71 Coulombs, maintaining "Very Low" permeability. MIX-2, with 50% OPC and supplementary materials, showed improved performance with a charge of 223.02 Coulombs when PPF was added, a notable reduction. MIX-3 showed a decrease from 307.305 to 206.55 Coulombs after adding fibers, further enhancing its resistance. MIX-4 PPF, with the best results, saw its charge drop from 284.805 to 198.36 Coulombs. This mix, combining 50% OPC and 30% GGBS, proved to be the most effective, offering high durability in chloride-rich environments.

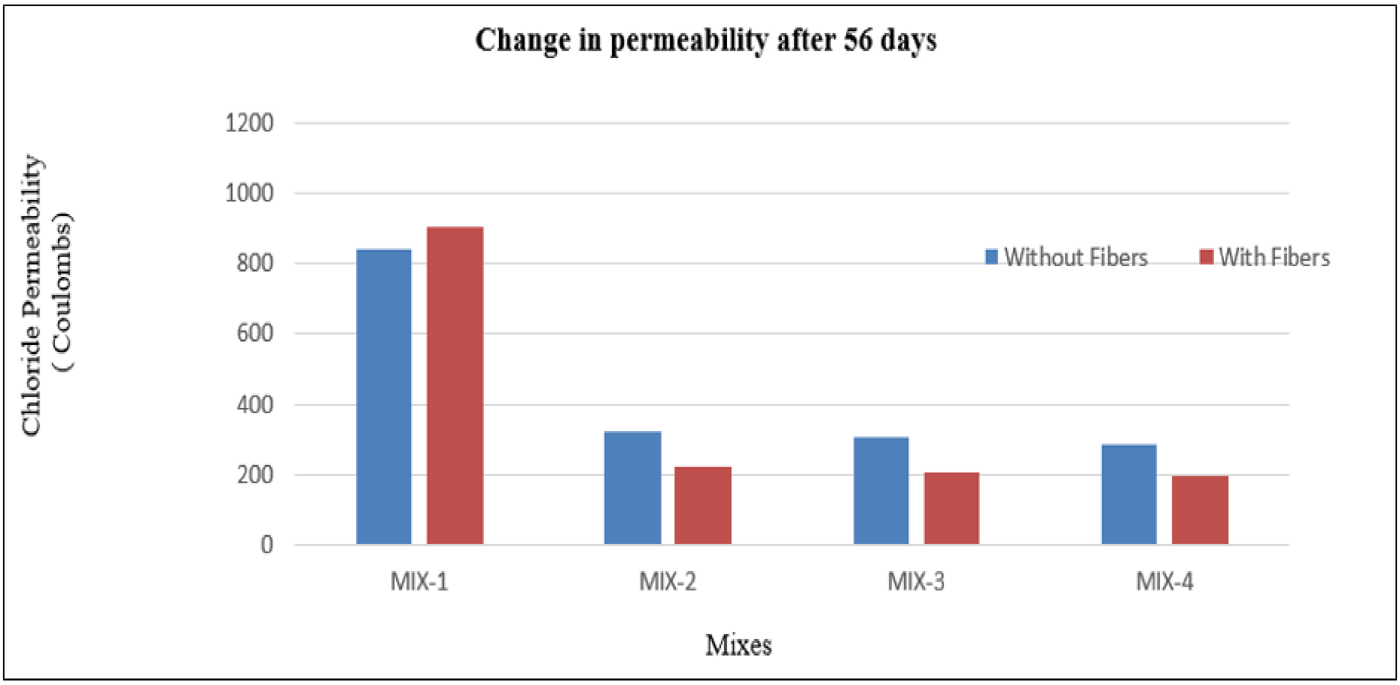

Fig 15 Variations in Permeability after 56 days curing for with and without fiber mixes

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VI. CONCLUSIONS

The study provides valuable insights into the chloride penetration behaviour of sustainable Quaternary Blended Self-Compacting Concrete (QBSCC) with and without polypropylene fiber reinforcement.

- The substitution of additional cementitious materials for 100% cement resulted in improved flow properties of the mixture, although the inclusion of polypropylene fiber decreased its rheological qualities.
- Mix-2, distinguished by its higher content of fly ash, consistently demonstrated superior rheological characteristics regardless of fiber presence. This can be credited to the formation of a lubricating layer by fine particles, enabling cement particles to move more smoothly and with less resistance.
- The feasibility of producing self-compacting concrete (SCC) is significantly enhanced by substituting cement with various mineral admixtures such as fly ash, GGBS, and silica fumes. This substitution not only improves overall performance but also leverages synergistic effects among these mineral additives.
- Experimental results indicated that a high content of fly ash initially led to a slow pozzolanic reaction and lower early-age strength. However, over time, the pozzolanic activity increased, contributing to strength development, while silica fume exerted its influence primarily in the early stages of concrete curing.
- Furthermore, the addition of fibers further enhanced the mechanical properties of the concrete by creating a bridging effect, which significantly boosted its strength.
- After a curing period of 56 days, QBSCC mixes exhibited higher strength compared to control mixes. This enhancement can be attributed to the improved pozzolanic reaction and the combined effects of the various admixtures utilized in the mixes.
- Among all the mixes tested, Mix-4 and Mix-4PPF, with and without polypropylene fiber respectively, demonstrated the highest strength, whereas Mix-1 exhibited the lowest strength in comparison to the others.

➢ *Rapid Chloride Penetration Test*

- The results of the rapid chloride permeability test (RCPT) at 28 and 56 days for various Quaternary Blended Self-Compacting Concrete (QBSCC) mixes without fibers indicate significant improvements in chloride resistance when compared to the control mix (MIX-1) consisting of 100% Ordinary Portland Cement (OPC). These significant reductions in passed charges for MIX-2, MIX-3, and MIX-4 compared to MIX-1 illustrate the effectiveness of incorporating supplementary cementitious materials (SCMs) like SF, FA, and GGBS in enhancing concrete durability. The inclusion of these SCMs markedly decreases the permeability of the concrete, boosting its resistance to chloride ion penetration and potentially extending the lifespan of concrete structures subjected to harsh environmental conditions.
- Among the tested mixes, MIX-4 stands out with the greatest reduction in passed charges (66.17% at 56 days), indicating the lowest chloride ion permeability and hence the best potential durability. Therefore, MIX-4 is deemed the most suitable for construction projects, particularly in environments where concrete is exposed to chloride ions, such as marine structures or areas with deicing salt applications. The high replacement level of SCMs in MIX-4, including 30% GGBS, 10% SF, and 10% FA, significantly contributes to its superior performance in reducing permeability.
- The RCPT results for QBSCC mixes with fibers indicate that MIX-4 PPF, comprising 50% OPC, 10% SF, 10% FA, 30% GGBS, and 0.2% PPF, demonstrates the highest resistance to chloride ion penetration among the tested mixes, with the lowest average charge values at both 28 and 56 days. MIX-3 PPF and MIX-2 PPF also show excellent performance, significantly reducing chloride permeability compared to MIX-1 PPF. MIX-1 PPF, although classified as very low permeability, exhibits the highest charge values, indicating it is less effective than the other mixes. Thus, for construction projects requiring enhanced durability and long-term resistance to chloride-induced corrosion, MIX-4 PPF is the most suitable option, providing superior performance and ensuring the longevity of the structure.
- The addition of polypropylene fibers (PPF) to concrete mixes significantly reduces permeability to chloride ions after 28 days of curing. This improvement is consistent across all mixes tested, with reductions ranging from 8.16% to 20.16% in RCPT (Rapid Chloride Penetration Test) results. MIX-4, incorporating 50% OPC, 10% SF, 10% FA, and 30% GGBS along with PPF, exhibits the lowest permeability and highest resistance to chloride-induced corrosion among the mixes studied. Therefore, MIX-4 PPF is recommended for applications demanding high durability and low permeability, particularly in aggressive environmental conditions.
- The inclusion of polypropylene fibers (PPF) in concrete mixes has shown notable benefits in reducing chloride ion permeability, as evidenced by the Rapid Chloride Permeability Test (RCPT) results at 56 days. While MIX-1 PPF demonstrated a minor increase in permeability compared to MIX-1, mixes incorporating supplementary cementitious materials (SCMs) such as silica fume (SF), fly ash (FA), and ground granulated blast furnace slag (GGBS) showed significant reductions in passed charges with PPF. MIX-4 PPF, specifically composed of 50% OPC, 10% SF, 10% FA, 30% GGBS, and 0.2% PPF, exhibited the lowest average passed charge, indicating the highest resistance to chloride penetration among the tested mixes. This makes MIX-4 PPF particularly suitable for applications demanding high durability and low permeability, particularly in aggressive environments prone to chloride exposure.

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