© June 2026 | IJIRT | Volume 13 Issue 1 | ISSN: 2349-6002

Effect of Admixture Combinations on the Fresh and Hardened Properties of Self-Compacting Concrete

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Abstract—**Self-Compacting Concrete (SCC) is an innovative construction material that flows under its own weight without the need for mechanical vibration, making it ideal for complex and heavily reinforced structural elements. This study investigates the combined effect of chemical admixtures superplasticizer and viscosity modifying agent (VMA) alongside mineral admixtures such as fly ash and silica fume on the fresh, mechanical, and durability properties of SCC. Three Mix-variations were prepared: a control Mix-with only cement, a binary blend with fly ash, and a ternary blend with both fly ash and silica fume. All mixes were designed with a low water-to-binder (w/b) ratio of 0.31–0.35 and tested for fresh properties (slump flow, V-funnel, L-box), strength characteristics (compressive, split tensile, flexural), and durability performance (RCPT and water absorption). The results showed that the inclusion of fly ash improved flow ability and long-term strength, while the addition of silica fume enhanced cohesiveness, early strength, and durability. Among all mixes, the ternary blend (Mix-3) exhibited superior performance with a slump flow of 755 mm, L-box ratio of 0.96, compressive strength of 51.3 MPa at 28 days, and the lowest RCPT value of 890 coulombs, indicating very low permeability. These improvements were attributed to the synergistic effect of the fine particles and pozzolanic reactions of the mineral admixtures, combined with the optimized dosage of chemical admixtures.**

Index Terms—**Self-compacting concrete; viscosity modifying agent (VMA); Mechanical properties; Durability studies; Admixtures.**

I. INTRODUCTION

With rapid advancements in concrete technology, the demand for performance-oriented concrete mixes has grown significantly [1]. SCC offers numerous advantages such as reduced labor costs, better surface finishes, reduced noise levels on construction sites, and improved durability due to the absence of vibration-induced segregation. However, achieving these benefits consistently across different site conditions and material sources depends largely on the intelligent selection and combination of admixtures [2].

Superplasticizers (especially polycarboxylate ether-based) are used to impart high fluidity at low water content, which is essential for SCC. VMAs, on the other hand, help maintain homogeneity and minimize bleeding and segregation [3]. Incorporating mineral admixtures such as fly ash, silica fume, or ground granulated blast furnace slag (GGBS) further enhances properties like compressive strength, durability, and environmental sustainability [4].

While the individual effects of these admixtures have been widely studied, their combined effects particularly in varying dosages remain a relatively under-researched area. There is a pressing need to understand how different admixtures interact, influence fresh and hardened properties, and contribute to the overall performance of SCC. Identifying optimum combinations and proportions can lead to more cost-effective, durable, and eco-friendly SCC mixes [5].

Concrete remains the most widely used construction material worldwide, primarily due to its excellent compressive strength, durability, and adaptability to various forms and functions. As infrastructure demands grow and architectural complexities increase, there is a need for concrete mixes that can perform optimally without extensive mechanical compaction or vibration [6]. One such innovation that has revolutionized modern construction practices is Self-Compacting Concrete (SCC). Developed in the late 1980s in Japan to address issues related to the shortage of skilled labor and the need for high-performance concrete in densely reinforced structures, SCC has since become an essential material in both precast and in-situ concrete applications [7,8].

SCC is a highly flowable, non-segregating concrete that spreads into place under its own weight and completely fills formwork, even in the presence of congested reinforcement, without the need for mechanical vibration. The fundamental properties of SCC high flowability, passing ability, and resistance to segregation are achieved through careful proportioning of materials and the strategic use of chemical and mineral admixtures [9-11]. The inclusion of these admixtures is critical in reducing the water-to-binder ratio while maintaining the desired rheological behavior and mechanical performance.

Traditionally, the use of individual admixtures such as superplasticizers and viscosity modifying agents (VMAs) has been effective in achieving the required workability of SCC. However, the complex interaction between different admixtures, particularly when used in combination, is less understood and often underexplored [12-15]. Combining different types of admixtures offers the potential for enhanced performance through synergistic effects, but it also poses challenges due to possible incompatibilities or adverse chemical reactions. Therefore, a systematic study of the effect of combined admixtures on the characteristic properties of SCC is essential for developing optimized Mix-designs that cater to both structural and durability requirements [16-20].

Numerous researchers have contributed to the understanding of SCC and its admixture-based enhancements. Okamura and Ouchi (2003) [3], pioneers of SCC, demonstrated the need for high deformability, resistance to segregation, and good passing ability to define SCC's performance parameters. Their work laid the foundation for subsequent SCC development across the globe [14,15].

Khayat (1999) [2] explored the role of viscosity modifiers in improving the segregation resistance of highly fluid concrete. His findings emphasized the importance of balancing flow ability and stability through chemical admixtures. Similarly, EFNARC (European Federation of National Associations Representing for Concrete) [34] has provided detailed guidelines for the Mix-design and testing of SCC, including the acceptable limits for slump flow, T500 time, V-funnel time, and L-box ratios, all of which are influenced by admixture types and dosages.

In studies by Domone (2006) [1], the influence of superplasticizer dosage on the flowability and compressive strength of SCC was extensively documented, with findings showing that overdosage can lead to segregation while underdosage limits workability. Dinakar et al. (2008) [4] investigated the use of fly ash and silica fume in SCC and reported improvements in both fresh and hardened state properties, especially when used in appropriate combinations.

Several other studies have focused on the compatibility of different admixtures. For instance, research by Jain and Neithalath (2010) [5] indicated that the simultaneous use of polycarboxylate superplasticizers and VMAs could produce synergistic improvements in SCC workability and cohesion. However, they also cautioned that improper dosages could result in negative effects such as excessive air entrainment or delayed setting times. These studies underline the critical role of combinatorial admixture effects and highlight the necessity of in-depth investigations to evaluate the optimal performance range of SCC [21-23].

II. OBJECTIVES OF THE WORK

The objective of this study lies in its potential to contribute to the optimization of SCC Mix-design using readily available admixtures. Understanding the role of admixture combinations not only enhances the performance of SCC but also promotes sustainable construction practices by enabling the use of supplementary cementitious materials like fly ash and silica fume. Moreover, improved workability and durability characteristics can lead to extended service life of structures, reduced maintenance costs, and lowered environmental impact. By focusing on the influence of combined admixtures, this study addresses a gap in current research and provides engineers, researchers, and construction professionals with practical knowledge to better utilize SCC in real-world applications.

This study aims to evaluate the effect of combined chemical and mineral admixtures on the performance of SCC. Various Mix-combinations using superplasticizers, VMAs, fly ash, and silica fume are developed to assess their influence on fresh properties such as slump flow, T500 time, V-funnel time, and L-box ratio. The research also examines the mechanical performance, including compressive, split tensile, and flexural strength, along with modulus of elasticity. Additionally, durability characteristics like chloride resistance and water absorption are studied. The goal is to identify the most effective admixture combinations for achieving high workability, strength, and durability in SCC.

III. MATERIALS USED IN THE STUDY

The performance of SCC depends significantly on the quality and proportioning of its constituent materials. In this study, carefully selected materials were used to develop various SCC mixes incorporating combinations of chemical and mineral admixtures. All materials conform to relevant IS and ASTM standards to ensure consistency and reliability in results. The following subsections describe the materials used in detail:

3.1 Cement

Ordinary Portland Cement (OPC) of 53 grade, conforming to IS: 12269-2013, was used as the primary binder. It is known for its high early strength and compatibility with various chemical admixtures. The cement was tested for specific gravity, fineness, setting time, and compressive strength to ensure suitability for SCC production.

3.2 Fine Aggregate

Natural river sand conforming to Zone II as per IS: 383-2016 was used as the fine aggregate. The sand was clean, well-graded, and free from organic impurities. The specific gravity, water absorption, and fineness modulus were determined to ensure uniformity across mixes. Fine aggregate played a crucial role in achieving the required flowability and passing ability in SCC.

3.3 Coarse Aggregate

Crushed granite aggregates of 12 mm maximum size were used to enhance the passing ability of SCC through congested reinforcement. The aggregates conformed to IS: 383-2016 specifications. A combination of 12 mm and 10 mm down-sized aggregates was used in suitable proportions to achieve better packing density and minimize interparticle friction [33]. The coarse aggregate properties, such as specific gravity, water absorption, and impact value, were evaluated prior to Mix-design.

3.4 Water

Potable water, free from harmful salts and impurities, was used for mixing and curing, as per IS: 456-2000 [35]. The water-to-binder (w/b) ratio was kept low to maintain strength and durability, with flowability compensated using admixtures.

3.5 Chemical Admixtures

To achieve the desired rheological properties of SCC, two types of chemical admixtures were used:

- Superplasticizer (SP): A polycarboxylate ether (PCE)-based superplasticizer conforming to IS: 9103-2019 was used to achieve high workability with a low w/b ratio. The SP significantly improved the flowability of concrete without segregation and was selected based on its compatibility with the cement used.
- Viscosity Modifying Agent (VMA): A commercially available VMA was used to enhance the cohesiveness and segregation resistance of the concrete mix. It was particularly effective in controlling bleeding, especially in high-fluidity SCC mixes.

The dosage of chemical admixtures was varied systematically in different Mix-combinations to study their individual and synergistic effects on fresh and hardened concrete properties.

3.6 Mineral Admixtures

Two mineral admixtures were used as supplementary cementitious materials (SCMs) to improve the performance and sustainability of SCC:

- Fly Ash (FA): Class F fly ash obtained from a local thermal power plant was used. It conforms to IS: 3812 (Part 1) – 2013. Fly ash enhances the workability and long-term strength of concrete while also contributing to sustainability by reducing cement content.

- Silica Fume (SF): Densified silica fume conforming to ASTM C1240 was used in partial replacement of cement. It enhances the microstructure, reduces porosity, and improves the mechanical and durability properties of SCC due to its high pozzolanic activity.

3.7 Mix-proportions

The Mix-proportioning table outlines three SCC Mix-variations designed to evaluate the influence of combined chemical and mineral admixtures on fresh and hardened properties. Mix-1 serves as the control mix, composed solely of cement (400 kg/m³) as the binder, along with a polycarboxylate ether-based superplasticizer (6 kg/m³ or 1.5% of binder weight). This Mix-maintains a water-to-binder (w/b) ratio of 0.35, using 140 kg/m³ of water, and includes 720 kg/m³ of coarse aggregates and 850 kg/m³ of fine aggregates. This baseline Mix-represents conventional SCC with adequate workability but limited enhancements in durability or sustainability.

Mix-2 introduces fly ash (100 kg/m³) as a partial replacement for cement, reducing the cement content to 350 kg/m³ while maintaining the total binder content at 450 kg/m³. This Mix-uses a slightly higher superplasticizer dosage (7.5 kg/m³) and incorporates a viscosity modifying agent (1.0 kg/m³) to ensure stability and resistance to segregation due to the increased powder content. The coarse aggregate content is slightly reduced to 700 kg/m³, while the fine aggregate content is increased to 870 kg/m³ to enhance the mix's passing ability. The w/b ratio is slightly reduced to 0.31, benefiting from the improved workability provided by the fly ash and admixtures.

Mix-3 further modifies the binder composition by incorporating both fly ash (100 kg/m³) and silica fume (50 kg/m³), reducing the cement content to 300 kg/m³ while keeping the total binder constant at 450 kg/m³. Silica fume, being highly pozzolanic and fine, contributes to strength gain and densification of the microstructure, thus enhancing durability. The superplasticizer and VMA dosages remain the same as in Mix-2 (7.5 kg/m³ and 1.0 kg/m³, respectively). The coarse aggregate content is slightly reduced to 680 kg/m³, and the fine aggregate is increased to 890 kg/m³, maintaining the required flowability and cohesion. Like Mix-2, the w/b ratio is maintained at 0.31. Table 1 presents the Mix-proportioning of self-compacting concrete.

Table 1: Mix-proportioning of self-compacting concrete

Material	Mix-1 (Control SCC)	Mix-2 (FA + SP + VMA)	Mix-3 (FA + SF + SP + VMA)
Cement (kg)	400	350	300
Fly Ash (kg)	0	100	100
Silica Fume (kg)	0	0	50
Water (kg)	140	140	140
Coarse Aggregate (kg)	720	700	680
Fine Aggregate (kg)	850	870	890
Superplasticizer (kg)	6 (1.5% of binder)	7.5 (1.5% of binder)	7.5 (1.5% of binder)
Viscosity Modifying Agent (kg)	0	1	1
Total Binder (kg)	400	450	450
Water/Binder Ratio	0.35	0.31	0.31

IV. TEST METHODS

To evaluate the performance of SCC with various combinations of chemical and mineral admixtures, a series of tests were conducted on both fresh and hardened concrete. The fresh concrete tests focused on assessing the essential self-compacting characteristics, while mechanical and durability tests were performed to understand strength development and long-term performance.

Fresh concrete properties were evaluated using standard methods recommended by EFNARC and ASTM. The slump flow test was conducted to determine the filling ability of SCC. A standard slump cone was filled and lifted vertically, and the average diameter of the concrete spread was measured. The T500 time, indicating viscosity, was also recorded as the time taken for the concrete to reach a 500 mm diameter spread. Ideally, slump flow values between

650 mm and 800 mm with T500 times between 2 to 5 seconds represent acceptable workability [24]. To further assess flow characteristics, the V-funnel test was performed, where concrete was poured into a V-shaped funnel, and the time taken for complete discharge was measured. Optimal flow times for SCC typically range from 6 to 12 seconds, indicating good viscosity and stability. The L-box test was used to evaluate the passing ability of SCC through congested reinforcement. The height ratio (H_2/H_1) between the flowing and resting concrete was measured, where values between 0.8 and 1.0 reflect excellent passing ability. Additionally, a Visual Segregation Index (VSI) was used to assess any visual signs of bleeding or aggregate separation during the slump flow test, helping determine the cohesiveness of the Mix-[25-27].

For hardened concrete, mechanical properties were assessed through compressive strength, split tensile strength, flexural strength, and modulus of elasticity tests. The compressive strength test, conducted in accordance with IS: 516 (Part 1/Sec 1) – 2021, involved casting and testing standard 150 mm cube specimens at 7, 28, and 56 days. This test helped compare strength gain among different Mix-variations. The split tensile strength test was carried out as per IS: 5816 – 1999 using 150 mm × 300 mm cylindrical specimens, which were loaded diametrically to evaluate tensile resistance, an important factor in crack resistance. For flexural performance, beam specimens of size 100 mm × 100 mm × 500 mm were subjected to two-point loading based on IS: 516 (Part 2/Sec 2) – 2021 to determine their resistance to bending. To assess the stiffness and elastic behavior of SCC, the modulus of elasticity test was conducted using strain gauges mounted on cylindrical specimens under axial loading, following IS: 516 (Part 5/Sec 1) – 2018, with stress–strain data plotted to determine the elastic modulus.

In terms of durability, two key tests were performed. The RCPT, as per ASTM C1202, was used to evaluate the resistance of SCC to chloride ion ingress a crucial factor in determining its long-term corrosion resistance in reinforced concrete structures. Disc specimens were subjected to a 60V DC voltage across sodium chloride and sodium hydroxide chambers for six hours, and the total charge passed (in coulombs) was measured. Coulomb values below 1000 indicate very low permeability, whereas values between 1000–2000 are considered low. To evaluate porosity and water absorption capacity, the Water Absorption Test was conducted according to IS: 1199 (Part 2) – 2018. In this method, oven-dried concrete specimens were weighed, immersed in water for 24 hours, and weighed again to calculate the percentage of water absorbed.

V. RESULTS AND DISCUSSIONS

5.1 Fresh properties of SCC

The slump flow test is a key indicator of the filling ability of Self-Compacting Concrete (SCC), while the T500 time reflects its viscosity. The control Mix-(Mix-1) achieved a slump flow of 670 mm and a T500 time of 4.8 seconds, indicating moderate flowability and relatively higher viscosity. In contrast, Mix2, which incorporated fly ash and a VMA, showed a higher slump flow of 740 mm and a lower T500 time of 3.7 seconds. The improved flowability in Mix-2 can be attributed to the spherical shape and fine nature of fly ash particles, which reduce internal friction and improve lubrication within the mix. Moreover, the VMA played a vital role in maintaining the cohesiveness of the mix, ensuring that increased flow did not lead to segregation [28-30].

Mix-3, which combined both fly ash and silica fume along with chemical admixtures, achieved the highest slump flow of 755 mm and the lowest T500 time of 3.5 seconds. This indicates that Mix-3 possessed excellent filling ability and a very stable, fluid consistency. Silica fume, despite its ultra-fine particle size and high surface area, helped refine the pore structure and contributed to a more cohesive matrix. The combined effect of fly ash and silica fume enhanced both flow and cohesiveness, a critical factor in producing high-quality SCC. Thus, Mix-3 exhibited the most favorable slump flow and T500 performance, making it ideal for use in congested or heavily reinforced structural elements.

The V-funnel test is used to assess the flow time and viscosity of SCC, helping determine the rate at which concrete flows through a narrow opening without segregation. A shorter V-funnel time indicates lower viscosity and better flow, while longer times may suggest potential workability issues. In this study, Mix-1 (control) recorded the highest flow time of 12.1 seconds, which is on the upper acceptable limit. This result indicates that although the Mix-was workable, it had higher internal resistance due to the absence of any mineral admixture, leading to increased paste thickness and sluggish flow.

Mix-2, which included fly ash and VMA, demonstrated a reduced flow time of 9.5 seconds. The reduced viscosity in Mix-2 is a result of fly ash's ball-bearing effect, which enhances particle dispersion and flow while maintaining cohesion through the action of the VMA. The VMA helped counteract any potential segregation due to increased flowability, thereby maintaining stability.

The most favorable results were observed in Mix-3, which had a flow time of 8.7 seconds well within the optimal range for SCC. The inclusion of silica fume, in combination with fly ash, not only reduced pore spaces but also contributed to a well-packed, lubricated matrix. This helped achieve smooth and consistent flow through the V-funnel. Hence, Mix-3 exhibited superior viscosity control and flow behavior, indicating excellent potential for use in projects requiring highly fluid yet stable concrete.

The L-box test evaluates the passing ability of SCC, especially its capability to flow through congested reinforcement without blocking or segregation. The test compares the height of concrete at the end of horizontal flow (H_2) with the initial height (H_1), and the ratio H_2/H_1 indicates performance. For SCC, values between 0.8 and 1.0 are acceptable, with higher values signifying better passing ability.

In this study, the control Mix-(Mix-1) achieved an L-box ratio of 0.82, just meeting the lower acceptable limit. This lower value suggests limited passing ability due to higher coarse aggregate content and lack of fly ash or VMA to reduce interparticle friction. Mix-2 performed better, achieving a ratio of 0.93, indicating excellent passing ability. This improvement can be attributed to the reduced coarse aggregate content and enhanced paste volume provided by fly ash, which helped in smoother navigation through obstructions.

The best performance was observed in Mix-3, with an L-box ratio of 0.96. The combined effect of fly ash and silica fume created a highly cohesive and lubricated paste that minimized the potential for blockage. The refined particle structure from silica fume and the improved flowability from fly ash enabled the concrete to pass smoothly around reinforcement bars. Overall, Mix-3 showed outstanding passing ability, making it most suitable for structural elements with dense rebar arrangements.

Table 2: Fresh properties of self-compacting concrete

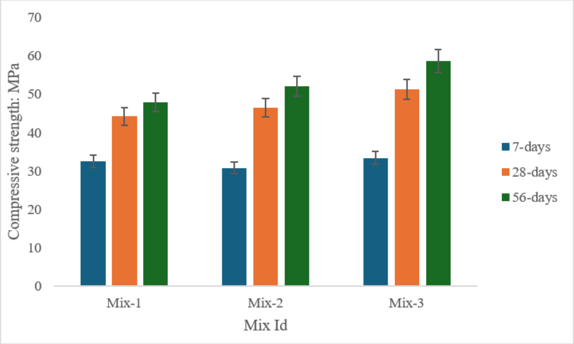
Test	Mix-1 (Control)	Mix-2 (FA + SP + VMA)	Mix-3 (FA + SF + SP + VMA)
Slump Flow (mm)	670	740	755
T500 Time (sec)	4.8	3.7	3.5
V-Funnel Time (sec)	12.1	9.5	8.7
L-Box Ratio (H_2/H_1)	0.82	0.93	0.96
VSI Rating	1 (Stable)	0 (Highly Stable)	0 (Highly Stable)

5.2 Compressive strength

Compressive strength is a primary parameter in assessing the load-bearing capacity of concrete. The strength development at 7, 28, and 56 days was analyzed for all three SCC mixes. Mix-1 (control) achieved a 28-day compressive strength of 44.2 MPa, increasing to 47.8 MPa at 56 days. While this result is satisfactory, it shows limited strength gain over time, likely due to the absence of supplementary cementitious materials [31,32].

Mix-2, which included 100 kg/m^3 of fly ash, displayed improved strength development with a 28-day strength of 46.5 MPa and a 56-day strength of 52.1 MPa. Fly ash contributed to a denser matrix and continued pozzolanic reaction beyond 28 days, which explains the enhanced long-term strength. The presence of superplasticizer and VMA helped in proper dispersion of cement particles and reduced water demand, improving strength characteristics.

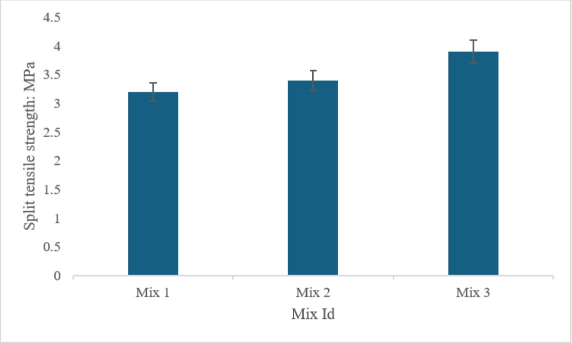
Mix-3 demonstrated the highest compressive strength across all ages, with 51.3 MPa at 28 days and 58.6 MPa at 56 days. The synergistic effect of fly ash and silica fume enhanced both early and long-term strength. Silica fume's ultrafine particles filled voids in the matrix, improving packing density and accelerating strength development. Thus, Mix-3 proves to be the most effective for structural applications requiring high strength and durability.

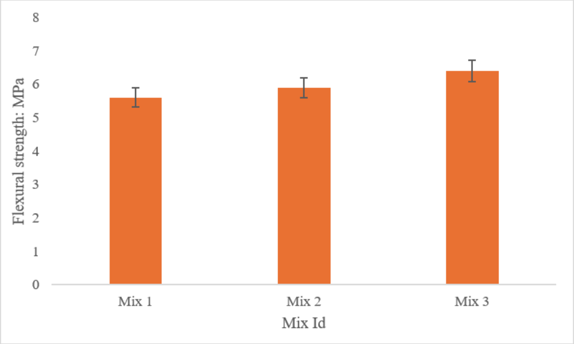


5.3 Split tensile and flexural strengths

Split tensile and flexural strength tests provide insight into the tensile capacity and ductility of concrete, which are important for crack resistance and serviceability. The 28-day split tensile strength for Mix-1 was 3.2 MPa, while Mix-2 and Mix-3 achieved 3.4 MPa and 3.9 MPa, respectively. The increase in Mix-2 is attributed to improved particle dispersion from fly ash, which enhances bonding between the cementitious matrix and aggregates. Mix-3 performed best due to the combined effects of silica fume and fly ash, both of which contribute to improved paste-aggregate interaction and refined microstructure.

In terms of flexural strength, Mix-1 reached 5.6 MPa, Mix-2 achieved 5.9 MPa, and Mix-3 recorded 6.4 MPa. Again, the presence of silica fume in Mix-3 was critical in improving the interfacial transition zone (ITZ) and reducing microcracks. Improved bond strength and homogeneity in the matrix contributed to better stress distribution and higher resistance to bending. These results confirm that Mix-3 not only offers enhanced compressive capacity but also improves overall toughness and cracking resistance of SCC.

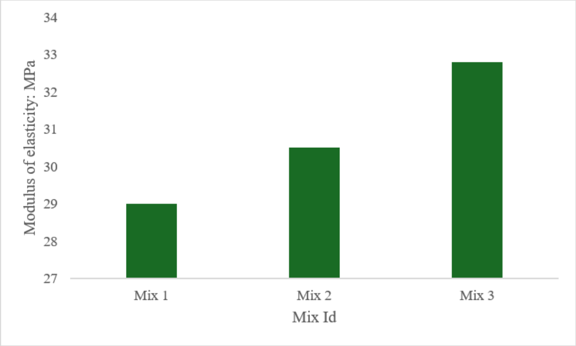




5.4 Modulus of elasticity

The modulus of elasticity reflects the stiffness and deformation behavior of concrete under load. It is critical in assessing structural deflection and load redistribution. Mix-1 showed a 28-day elastic modulus of 29.0 GPa, which is typical for conventional SCC. Mix-2 demonstrated a slight improvement with 30.5 GPa, due to better packing density and reduced porosity from the inclusion of fly ash.

Mix-3 showed the highest value at 32.8 GPa, indicating enhanced stiffness and lower deformation under stress. The presence of both fly ash and silica fume contributed to matrix densification and improved bonding between the paste and aggregates. These improvements lead to higher elastic recovery and structural efficiency. Hence, Mix-3 is suitable for structural applications requiring minimal deflections and higher service life.



5.5 Durability studies

Durability properties, particularly resistance to chloride ingress and water absorption, are essential for the long-term performance of reinforced concrete structures. The RCPT revealed that Mix-1 passed 2975 coulombs, indicating moderate permeability, which may pose a risk in aggressive environments. Mix-2, with fly ash, showed a significant improvement at 1820 coulombs, reflecting low permeability due to the pozzolanic reaction that refines pore structure and reduces connectivity.

Mix-3 displayed excellent durability with an RCPT value of 890 coulombs, placing it in the very low permeability category. The ultrafine silica fume significantly contributed to pore refinement and reduced ionic mobility within the matrix. Similarly, water absorption values decreased from 2.4% in Mix-1 to 1.8% in Mix-2, and 1.3% in Mix-3. This confirms that the combined use of mineral admixtures not only enhances mechanical properties but also minimizes moisture ingress, thereby reducing the risk of corrosion and extending service life. Among the three mixes, Mix-3 exhibited superior durability characteristics, making it ideal for long-term and aggressive exposure conditions.

Test Method	Mix-1	Mix-2	Mix-3
RCPT – Charge Passed (Coulombs)	2975	1820	890
Water Absorption (%)	2.4	1.8	1.3

VI. CONCLUSIONS

This study examined the influence of combined chemical (superplasticizer and viscosity modifying agent) and mineral admixtures (fly ash and silica fume) on the fresh, mechanical, and durability properties of SCC. The experimental results clearly indicate that the inclusion of fly ash and silica fume significantly improves the overall performance of SCC when compared to a control Mix-containing only cement. In terms of workability, all mixes satisfied the self-compacting requirements; however, the Mix-incorporating both fly ash and silica fume (Mix-3) exhibited superior flowability, passing ability, and stability, with slump flow, V-funnel, and L-box results well within EFNARC-specified limits. The synergistic action of fly ash, which enhances flowability, and silica fume, which increases cohesiveness, contributed to a highly workable and stable SCC mix.

In the hardened state, Mix-3 consistently outperformed the other mixes across all mechanical properties, including compressive strength, split tensile strength, flexural strength, and modulus of elasticity. The long-term strength gain in Mix-2 and Mix-3 highlights the continued pozzolanic activity of fly ash and the microstructure refinement provided by silica fume. Durability test results, including RCPT and water absorption, further confirmed that the binary combination of fly ash and silica fume in Mix-3 provided the highest resistance to chloride ion penetration and lowest water absorption, classifying it as very low in permeability. Overall, the study concludes that the combined use of fly ash and silica fume, along with proper dosages of superplasticizer and VMA, results in an SCC Mix-that not only meets fresh property criteria but also achieves superior strength and durability. This optimized Mix-design offers a practical, sustainable, and high-performance solution for modern concrete construction, particularly in heavily reinforced or durability-critical structural elements.

VII. FUTURE SCOPE

While the present study demonstrates the effectiveness of combining fly ash, silica fume, and chemical admixtures in improving the performance of SCC, several areas remain open for further investigation. Future research can focus on exploring other supplementary cementitious materials such as GGBS, metakaolin, or rice husk ash, either individually or in combination, to evaluate their influence on the fresh and hardened properties of SCC. Investigating the use of nano-materials (e.g., nano-silica or nano-alumina) could further enhance the microstructure and durability aspects of SCC.

Additionally, the long-term performance of SCC under aggressive environmental conditions such as marine exposure, freeze-thaw cycles, and sulphate attack needs to be studied in detail. Incorporating non-destructive testing techniques like ultrasonic pulse velocity (UPV), rebound hammer, or electrical resistivity could provide insights into the in-situ behavior and durability monitoring of SCC over time. Furthermore, the structural behavior of SCC in reinforced concrete elements, including bond strength with steel, shrinkage, and creep characteristics, should be evaluated.

Lastly, to make SCC more sustainable and cost-effective, studies can focus on low-carbon binder systems using industrial by-products, fiber reinforcement for ductility improvement, and life-cycle assessment (LCA) to quantify the environmental benefits. These explorations will broaden the applicability of SCC in high-performance, green, and durable construction practices.

ACKNOWLEDGEMENTS

The authors are thankful to the ABR College of engineering and Technology for infrastructure, lab facilities, and constant support for this Research work.

Declarations: The authors declared that there is no conflict-of-interest statement to publish this paper.

Conflicts of interest: The authors declare that there is no conflict of interest.

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