Rheological and Mechanical Behavior of Self-Compacting Concrete with Mineral Admixtures

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Abstract. The fresh, mechanical, bond, and acid resistance performances of concrete containing Flyash and Palm Oil Fuel Ash (POFA) are studied here as partial cement replacement materials. Ten mix proportions prepared by varying combined replacement levels from 10% to 50%. The results showed that all the blended mixes achieved better workability than conventional concrete, as evidenced from the slump values in the range of 705–729 mm with improved filling and passing ability. Mechanical strength at 7, 14, and 28 days of age demonstrated that the compressive strengths obtained for moderate replacement levels, 10–30% SCM blends, were higher than control, while Trial 4 presented the highest compressive strength of 27.52 MPa at 28 days. The results of the bond behaviour through pull-out tests indicated an improved steel–concrete interaction in SCM mixes, where Trial 7 reported the maximum bond strength of 7.72 MPa. The durability performance, depicted through hydrochloric acid exposure, revealed a reduction in weight loss for all blended mixes, and the minimum deterioration of 8.16% was recorded for Trial 7. Overall, this study demonstrates that the combined use of Flyash and POFA significantly enhances workability, strength development, bond characteristics, and acid resistance and sustainable supplementary cementitious materials.

1 Introduction

SCC has revolutionized the construction practice through the provision of a highly workable mixture that flows under self-weight without the need for mechanical vibration. This innovation significantly improves construction speed, reduces manpower needs, and enhances the quality of densely reinforced structural elements [1]. SCC usually requires a slump flow of 650–800 mm, V-funnel time less than 12 seconds, and L-box blocking ratio above 0.8 to satisfy international fresh property requirements. The addition of FA and POFA has advanced the performance, sustainability, and economy of SCC [2]. These SCMs reduce cement usage apart from improving rheological performance, long-term strength gain,

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microstructural densification, and durability. A critical review is made herewith on the fresh state, mechanical, microstructural, and durability properties of SCC under the influence of FA and POFA as per the latest research [3].

Flyash's spherical particle shape, fineness, and pozzolanic reactivity have made it one of the most popular industrial by-products in SCC. Adding FA at replacement levels of 20–60% improves the workability of SCC considerably. High-volume flyash (HVFA) SCC, which usually contains 50–60% FA, exhibits better passing ability, less superplasticizer requirement, and lower plastic viscosity[4]. Increasing the amount of FA from 0% to 50% can yield slump flows exceeding 700 mm with a reduction in dosage of superplasticizer of 10–25%. This reduction is due to the "ball-bearing effect" of the smooth, glassy particles of FA. Ground flyash (GFA) with a Blaine fineness of more than 400 m^2/kg outperforms normal FA having a fineness of approximately 250–300 m^2/kg due to its increased particle packing density and reduced tendency for segregation[5]. A minimum level of fines, around 500–550 kg/m^3, in SCC mixes containing FA, has been found to be required for maintaining stability and preventing bleeding [6].

The utilization of POFA, a renewable by-product produced from the combustion of oil palm residues, has received a great deal of attention in SCC and the development of sustainable concrete. The raw POFA typically possesses high carbon content with a porous texture and can adversely affect workability; on the other hand, POFA treated thermally or by grinding improves significantly [7]. MT-POFA or heat-treated POFA with fineness more than 350 m^2/kg has attained significant improvements in rheological properties. POFA replacement from 10 to 30% is normally used in SCC. At lower levels (10–15%), POFA slightly reduces slump flow by about 20 to 40 mm, but the values are within the acceptable criteria for SCC. At higher replacement levels (>20%), 5 to 15% of an increase in superplasticizer dosage may be required to develop targeted workability. However, even at 30% replacement, POFA-based SCC mixes exhibited V-funnel times less than 15 s and L-box ratios more than 0.75, indicating acceptable flow characteristics [8].

When used together, FA and POFA act to neutralize each other's deficiencies due to their complementary properties. While POFA's amorphous silica aids in microstructural densification, FA improves flowability. It has been discovered that SCC mixtures with a single mineral admixture have less rheological stability than ternary blends of FA and POFA [9]. 40% FA + 10% POFA or 30% FA + 20% mixtures POFA complies with EFNARC guidelines and achieves slump flows between 680 and 760 mm. These blends exhibit excellent flowability, with T50 slump flow times of less than 4 s. Synergy between FA and POFA optimizes the particle-size distribution, helps reduce the yield stress, and improves overall cohesiveness of the SCC [10].

Mechanical properties of SCC incorporating FA and POFA are influenced by various parameters such as replacement level, fineness, water–binder ratio that is usually in the range of 0.30–0.45, and curing conditions. Compressive strength trends reported in the literature reflect that FA contributes to long-term strength development due to the slower pace of its pozzolanic reaction [11]. HVFA SCC mixtures containing 50–60% FA can have lower early-age compressive strength but may record substantial strength gain at later ages. Compressive strengths as high as 10–20% were recorded for the ground FA mixtures when compared to unground mixes at 28 and 90 days [12].

POFA, when used alone, is usually restricted to 10% replacement to avoid losses in compressive strength because of its highly porous texture. Compressive strength losses of 5–12% have been reported for POFA contents greater than 20%. However, in combination with FA, SCC mixtures can attain a very high total replacement percentage of combined FA and POFA without sacrificing strength up to 60%. It is possible for a ternary blend consisting of 40% FA + 20% POFA to attain 28-day compressive strengths in the range of 45–55 MPa, which is equal to, or even higher than, control SCC mixes [13]. These enhancements result from the creation of secondary C–S–H gel through pozzolanic reactions, pore refinement, and enhanced packing density.

The trend of tensile strength and flexural strength also generally follows the pattern of compressive strength. SCC mixes with FA at 20–40% replacement normally results in a 5–15% improvement in tensile strength at later ages by showing an improved microstructure with reduced connectivity of pores. POFA, up to 10–15%, increases the tensile strength by 3–8% because of increased bond strength between the cement paste and aggregates. Ternary blends often give better performance; for example, mixes containing 30% FA + 10% POFA have demonstrated flexural strength ranging from 6.0 to 6.8 MPa compared to 5.5 MPa for conventional SCC [14]. However, excessively high cement replacement or poorly processed POFA can decrease the early-age strengths due to a slower rate of reaction or insufficient hydration.

While FA and POFA have been widely used in SCC, numerous critical research gaps still exist. Current research has focused on studying either FA or POFA separately, with little consideration of high-volume binary or ternary blends, leaving the effects of combined FA-POFA systems largely unknown. Moreover, there is no standardized guideline on how to process FA and POFA, especially in terms of fineness levels, grinding duration, and particle size distribution, as a result, inconsistent performances are reported from study to study. Although enhancement of strength and workability has been reported in the majority of studies, most research relies on qualitative microstructural observations, with a lack of sufficient quantitative correlations between pore refinement, hydration products, and mechanical properties.

2 Materials

The materials used are OPC 33 grade, manufactured sand, fly ash, and palm oil fuel ash. The materials were selected in this study based on their physical, chemical, and performance characteristics related to the production of high-quality concrete. Knowledge of the basic properties is highly essential to predict the probable effects of each material on workability, strength development, and durability.

One of the common Portland cement grades on the market for general structural use is OPC 33 grade. According to the compressive test conducted on standard mortar cubes, it satisfies IS 269 requirements and has a characteristic compressive strength of 33 MPa at 28 days. With a specific gravity of 3.15, an initial setting time of 106 minutes, and a final setting time of 259 minutes, OPC 33 grade cement guarantees sufficient workability and handling time. A suitable rate of hydration is made possible by the fineness of 301 m²/kg. Tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) make up the primary phase composition. These elements work together to provide early and long-term strength, heat of hydration, and chemical resistance. OPC 33 grade is known to generate relatively lower heat of hydration than that of higher grades, thus being suitable in mixes where supplementary cementitious materials may be incorporated.

Because of its consistent quality, controlled gradation and lesser impurities compared with natural river sand, M-sand is used as the fine aggregate for concrete mixes. M-sand is produced by crushing hard granite rock. Its specific gravity is usually about 2.58, bulk density 1689 kg/m³ and water absorption 1% depending on the source. Most of the particles pass through the screen of 4.75 mm, and particle size distribution normally satisfies the requirements of Zone II of IS 383. The angular shape improves the mechanical interlock between the particles in concrete and enhances the durability and compressive strength of the concrete. On the other hand, M-sand concrete needs a little extra water compared to river sand mixes due to its abrasive texture.

Flyash is an industrial by-product generated during the combustion of coal in thermal power plants and is classified, based on its calcium content, as either Class F or Class C. Class F flyash, having a low calcium oxide content below 10%, is mainly used in structural applications in India due to its higher pozzolanic activity. FA possesses a specific gravity of 2.19, which is substantially lower than that of cement and helps in producing concrete of lower density. Its particles are spherical in nature with an extremely fine average fineness of 326 m^2/ kg. These properties enhance workability, reduce bleeding, and improve long-term strength of concrete through secondary C-S-H gel formation. The chemical composition of FA is rich in silica (SiO_2), alumina (AlO_3), and iron oxide (FeO_3), making it highly reactive pozzolana.

POFA, an agricultural waste by-product, is derived from the burning of palm oil residues. Raw POFA, therefore, contains unburnt carbon and porous particles, and needs to be sieved or ground to enhance its performance. The specific gravity and fineness of processed POFA are generally 2.3 and 351 m^2/kg, respectively, depending on the grinding method. POFA is rich in amorphous silica (60.15%) and can be considered a suitable supplementary cementitious material. Its irregular shape and porous surface will tend to increase water demand slightly when used in higher proportions. When POFA is processed correctly, it reduces permeability and refines pore structure, which increases durability, particularly in blended cement systems.

3 Mix Design and Methods

In order to evaluate the impact of flyash and palm oil fuel ash as partial cement replacement on the characteristics of self-compacting concrete, ten different concrete mixes were prepared for this study. Trials 2 through 10 have varying replacement levels of FA and POFA, ranging from 5% to 25%, while Trial 1 is the control mix with 100% Ordinary Portland Cement. The objective was to investigate the effects of varying proportions on durability, strength, and workability. Table 1. Shows the mix designation of various trials.

Table 1. Mix Designation

SI. No.	Trial	Description
1	Trial 1	Conventional Concrete
2	Trial 2	5% Flyash + 5% POFA + 90% Cement + 100% FA + 100 CA + 1% SP
3	Trial 3	10% Flyash + 10% POFA + 80% Cement + 100% FA + 100 CA + 1% SP
4	Trial 4	15% Flyash + 15% POFA + 70% Cement + 100% FA + 100 CA + 1% SP
5	Trial 5	20% Flyash + 20% POFA + 60% Cement + 100% FA + 100 CA + 1% SP
6	Trial 6	25% Flyash + 25% POFA + 50% Cement+ 100% FA + 100 CA + 1% SP
7	Trial 7	10% Flyash + 15% POFA + 75% Cement + 100% FA + 100 CA + 1% SP
8	Trial 8	10% Flyash + 20% POFA + 70% Cement + 100% FA + 100 CA + 1% SP
9	Trial 9	15% Flyash + 10% POFA + 75% Cement+ 100% FA + 100 CA + 1% SP
10	Trial 10	20% Flyash + 10% POFA + 70% Cement + 100% FA + 100 CA + 1% SP

4 Results and Discussion

4.1 Slump Cone

The slump values reflect that the addition of Flyash and POFA increased the flowability of the mixes over conventional concrete. Trial 1 had a value of 701 mm, with mixes containing combined replacements eventually recording higher slump values, peaking at 729 mm in Trial 6 (25% FA + 25% POFA). The slump clearly indicates the increased smoothness arising from the finer particle size and the pozzolanic action by FA and POFA. Trials 7 to 10 also showed high workability, within a slump range of 720–723 mm, with confirmation that blended replacements lead to higher self-compatibility without loss in cohesiveness. Fig. 1 slump cone value.

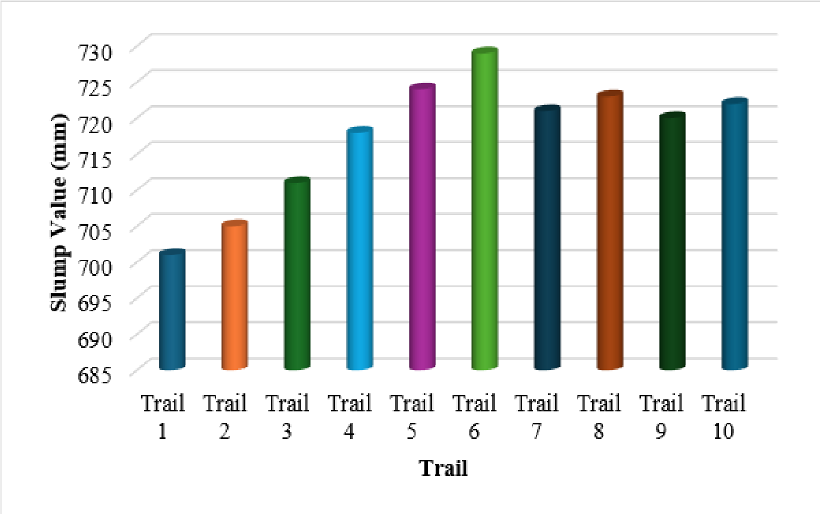

Fig. 1. Slump cone value

4.2 L-Box

From the L-Box test results, the passing ability of the mixes was found to decline progressively with increasing Flyash and POFA replacement levels. Again, both the control mix and Trial 2 achieved an excellent ratio of 0.82, which signifies good flow through reinforcement. The ratios continued to fall with increased replacement, the lowest ratio being in Trial 6 as 0.76 (25% FA + 25% POFA). This implies that the increase in viscosity is very minimal and the resistance to blocking reduced at higher replacement levels. However, in Trials 7–10, the mix ratios stayed within the range of 0.77 to 0.79, satisfying the minimum requirement to substantiate the passing ability of SCC in the presence of moderate combinations of FA–POFA. Fig. 2: L-box ratio

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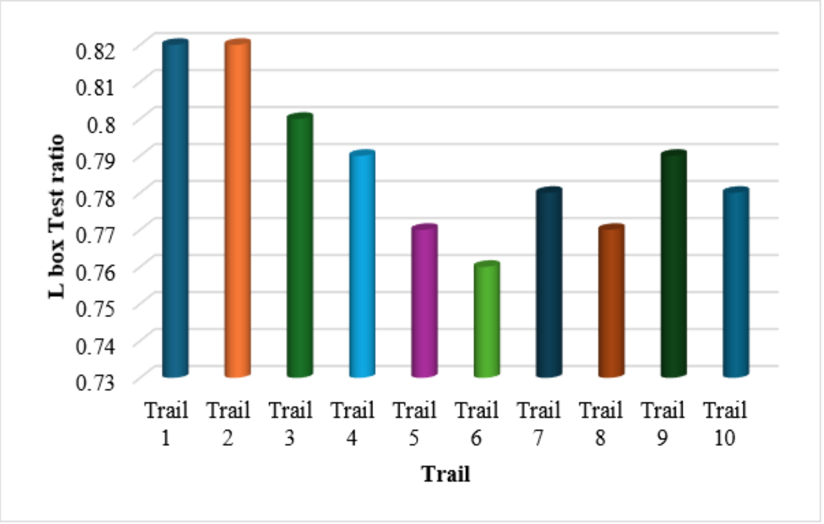

Fig. 2. L-box test results

4.3 V-Funnel

The V-Funnel results demonstrate that as flyash and POFA replacement increases, viscosity improves, and discharge occurs more quickly, flow time steadily decreases. Mixes with blended replacements produced faster flow, with the lowest time recorded in Trials 6 and 10 at 7.4 seconds. The control mix recorded 8.5 seconds. The smoother texture and smaller particle size of FA and POFA, which lessen internal friction in the mixture, are responsible for this improvement. Moderate replacement levels further improve the flow ability while maintaining stable viscosity appropriate for SCC applications, as demonstrated by trials 7 through 9, which also showed consistent times around 7.5–7.6 seconds. The V-funnel results are shown in Fig. 3.

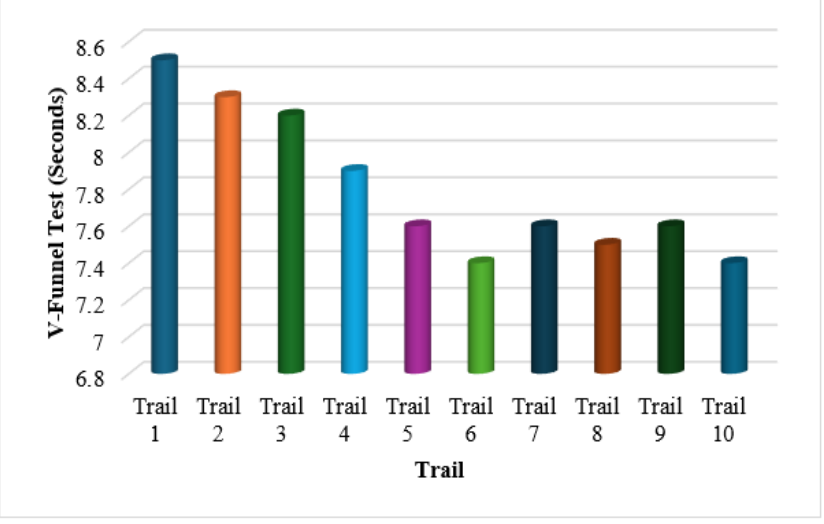

Fig. 3. V-funnel results

4.4 J-Ring

The J-Ring results show that the passing ability was somewhat decreased as Flyash and POFA replacement levels increased. The control mix had a value of 5.55 mm, but mixes with blended replacements had progressively higher values—a maximum of 5.95 mm in Trial 6—indicating greater flow resistance as a result of the higher powder content. Nevertheless, there is no indication of substantial blocking, and all the values from various trials stay within the acceptable range for SCC. It is confirmed that combined FA-POFA mixes at higher replacement levels still have sufficient segregation resistance and passing ability because all values from Trials 7 to 10 recorded readings in the range of 5.68 to 5.72 mm. The J-ring value is shown in Fig. 4.

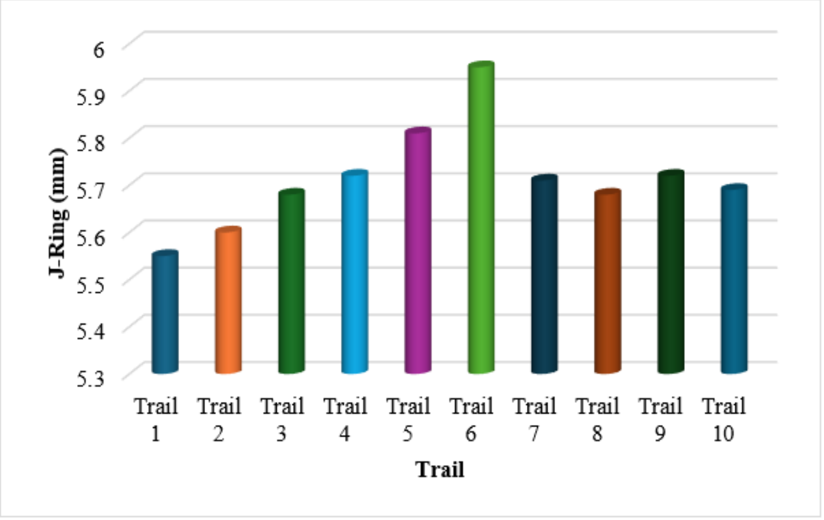

Fig. 4. J-ring test results

4.5 U-Box

The results obtained on the U-Box show that the filling ability of the mixes improved with higher replacements of Flyash and POFA. The height difference for the control mix was 25 mm, while the values increased with progressive replacements and reached a maximum of 36 mm in Trial 6. Such a trend shows reduced flow and slightly higher obstruction with higher powder contents. However, at moderate levels of replacements in Trials 7 to 10, the filling ability still remained acceptable for SCC, in the range from 30 to 33 mm. Overall, the results have pointed out that the FA–POFA blend has an influence on balancing viscosity and flow. Indeed, optimal performance occurs at mid-range replacement levels. Fig. 5 depicts the U-box value.

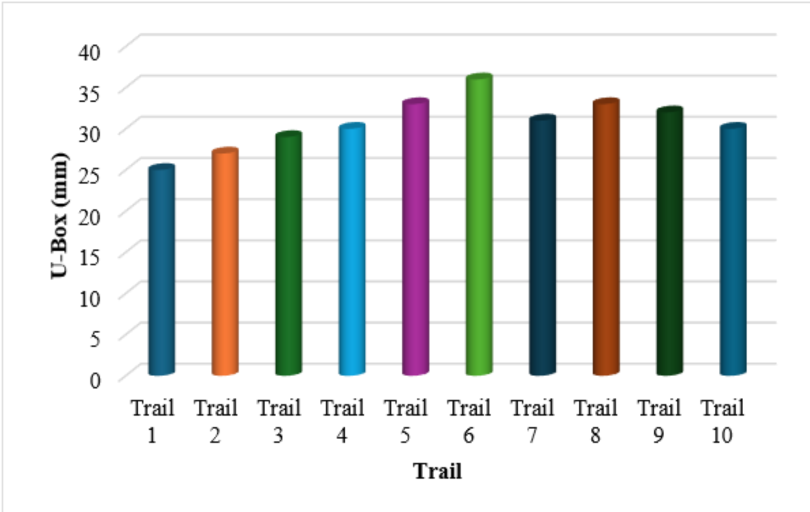

Fig. 5. U-box test results

4.6 Compressive Strength

Compressive strength test results indicate that partial cement replacement with Flyash and POFA improved strength development in comparison with conventional concrete. Whereas the control mix attained 25.95 MPa at 28 days, mixes containing blended replacements recorded marginally higher strengths, with the highest compressive strength of 27.52 MPa recorded for Trial 4 (15% FA + 15% POFA). Similarly, early-age strengths at 7 and 14 days showed consistent improvement in the mixes containing moderate replacements, reflecting beneficial pozzolanic action. The marginal reductions beyond 20% replacement, however, resulted in comparable 28-day strengths for all mixes to confirm that FA-POFA blends can be used to enhance performance without compromising structural adequacy. Fig. 6 shows the compressive strength.

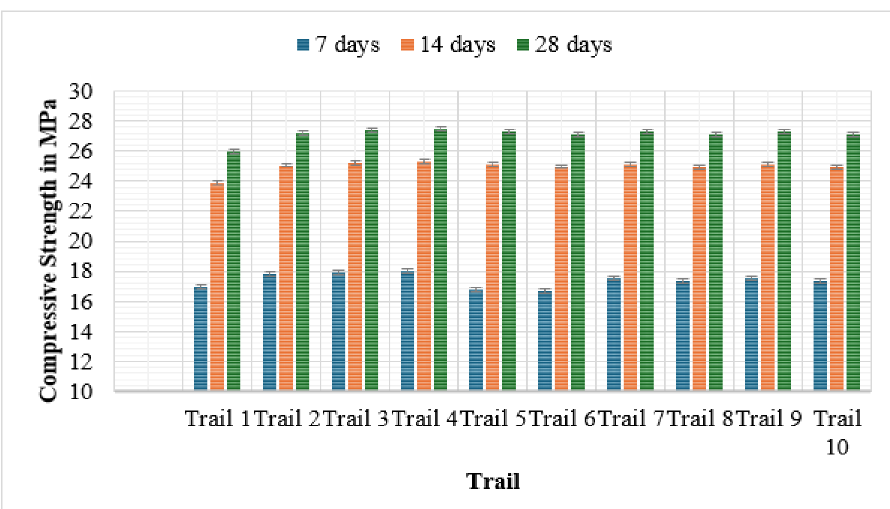

Fig. 6. Compressive strength test results

4.7 Pull Out

It is observed from the pull-out test results that the addition of Flyash and POFA improved the steel–concrete bond strength compared with the conventional mix. The bond strength of the control specimen was 7.16 MPa, while all the modified mixes recorded higher values, and the maximum bond strength of 7.72 MPa was obtained in Trial 7 (10% FA + 15% POFA). This can be attributed to the improved microstructure and interfacial transition zone provided by the pozzolanic action of FA and POFA. Though there was a marginal reduction at higher replacement levels, all the mixes exhibited tensile modes of failure, which confirm reliable bonding between steel and concrete. The pull-out test results are presented in Table 2.

Table 2. Pull-out test results

SI. No.	Mix	Description	Embedment length (mm)	Pull-out load at failure (kN)	Bond strength (MPa)	Failure mode
1	Trial 1	Conventional Concrete	200	56.32	7.16	Tensile
2	Trial 2	5% Flyash + 5% POFA + 90% Cement	200	57.39	7.30	Tensile
3	Trial 3	10% Flyash + 10% POFA + 80% Cement	200	58.06	7.38	Tensile
4	Trial 4	15% Flyash + 15% POFA + 70% Cement	200	59.51	7.57	Tensile
5	Trial 5	20% Flyash + 20% POFA + 60% Cement	200	58.63	7.45	Tensile
6	Trial 6	25% Flyash + 25% POFA + 50% Cement	200	57.03	7.25	Tensile
7	Trial 7	10% Flyash + 15% POFA + 75% Cement	200	60.72	7.72	Tensile
8	Trial 8	10% Flyash + 20% POFA + 70% Cement	200	58.98	7.50	Tensile
9	Trial 9	15% Flyash + 10% POFA + 75% Cement	200	59.67	7.59	Tensile
10	Trial 10	20% Flyash + 10% POFA + 70% Cement	200	57.83	7.35	Tensile

4.8 Acid Resistance

Hydrochloric acid resistance test results indicated that addition of Flyash and POFA generally reduced weight loss compared to conventional concrete. The measured weight loss for the control mix was 9.35%, while most blended mixes showed better performance due to increased pozzolanic activity as well as a denser microstructure. Accordingly, the highest acid resistance was manifested in Trial 7 (10% Flyash+15%POFA) with 8.16% weight loss, followed by Trial 4 with 8.32% and Trial 9 with 8.29% weight loss, indicating that balanced or moderately POFA-dominant blends have superior chemical durability. Mixes containing 20–30% total SCM content showed consistent improvement. But higher than optimum replacement resulted in reduction of effectiveness. Correspondingly, the highest measured weight loss was found in Trial 6 (25% Flyash+25%POFA) as 9.63%, even higher than that obtained from control. This is explained by the fact that beyond an optimum value, the amount of calcium hydroxide becomes insufficient to support secondary hydration, resulting in a more porous structure. However, it is deduced herein that moderate SCM blends significantly improve the acid resistance. Fig. 7 shows the percentage of weight loss in acid resistance test.

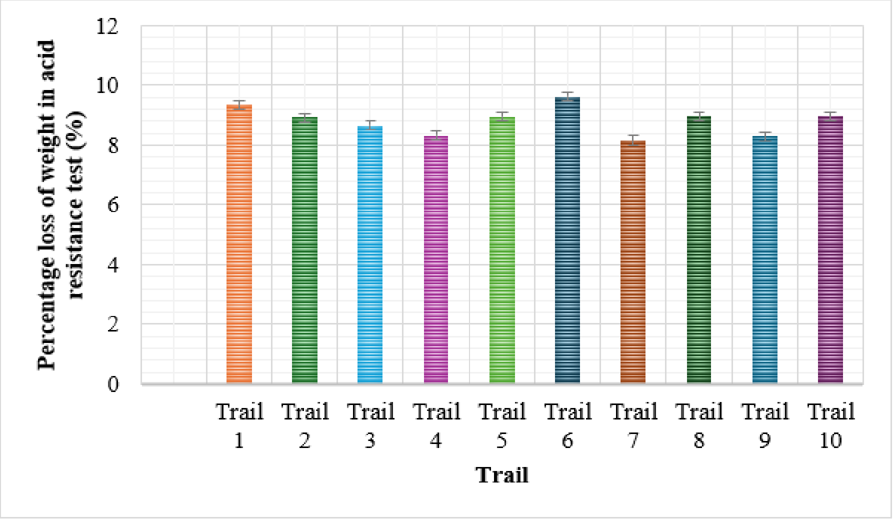

Fig. 7. Percentage of weight loss in acid resistance test

5 Conclusion

The results obtained from experimentation reveal that the addition of Flyash and POFA in different combinations improves fresh, mechanical, and durability performance significantly over and above the conventional mix. All the SCM-based mixes had slump values greater than that of the control: 705-729 mm versus 701 mm, indicating improved flowability. Similarly, the L-Box ratios, V-Funnel times, J-Ring values, and U-Box heights recorded confirm that these mixes possess acceptable filling and passing abilities for self-compacting characteristics. According to mechanical strength test results, moderate replacement levels—particularly Trials 3, 4, 7, and 9—perform better than the control at all curing ages and reach strengths between 27.28 and 27.52 MPa at 28 days.

The microstructural refinement enhanced by the pozzolanic action of Flyash and POFA is further validated by the pull-out test results. With a bond strength of 7.72 MPa and the highest pull-out load of 60.72 kN, Trial 7 demonstrated superior steel-concrete interaction. The blended mixes' durability under hydrochloric acid attack demonstrated a notably low weight loss, with Trial 7 outperforming the conventional mix at 8.16% as opposed to 9.35%. Overall, the study shows that the best mix of flyash and POFA, especially in the range of 20–30% total replacement, enhances workability, strength, bond performance, and acid resistance, making them appropriate for long-lasting, sustainable concrete production.

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