



SELF-COMPACTING CONCRETE WITH FLY ASH AND CALCIUM CARBIDE WASTE: BINDER CHEMISTRY, WORKABILITY, AND STRENGTH

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ABSTRACT

Purpose: This study investigated the suitability of fly ash (FA) and calcium carbide waste (CCW) as partial replacements for Portland cement (PC) in self-compacting concrete (SCC), focusing on their effects on material chemistry, fresh-state behaviour, compressive strength, and tensile strength.

Design/methodology/approach: Eleven SCC mixtures were prepared, comprising a control mixture and two replacement series incorporating 5–25% FA or CCW as partial replacements for PC. X-ray fluorescence (XRF) analysis was used to determine the chemical composition of FA and CCW. Fresh-state properties were assessed using slump flow and L-box ratio tests. Compressive strength was determined at 14, 28, and 56 days, while tensile strength was evaluated at 28 and 56 days.

Findings: XRF results showed that FA contained 59.04% SiO₂, 34.08% Al₂O₃, and 95.12% combined SiO₂ + Al₂O₃ + Fe₂O₃, indicating substantial pozzolanic potential. CCW contained 64.00% CaO but only 3.36% combined reactive oxides. Increasing FA replacement improved fresh-state performance, with slump flow increasing from 690 to 770 mm and the L-box ratio from 0.92 to 1.00 between 5% and 25% replacement. Conversely, CCW reduced slump flow from 680 to 640 mm and the L-box ratio from 0.90 to 0.80. Although replacement mixtures showed delayed early-age strength development, substantial later-age strength recovery was observed, particularly with FA. At 56 days, PC–FA5 and PC–FA10 achieved 44.0 MPa compressive strength compared with 40.0 MPa for the control. The highest tensile strength was 8.54 MPa at 15% FA, while 25% CCW achieved 7.73 MPa at 56 days.

Research limitations/Implications: The study was limited to the selected replacement levels, mixture proportions, curing conditions, and testing ages. Further investigation under different mixture designs, curing regimes, exposure conditions, and extended testing periods is required. The results highlight the importance of the chemical and physical characteristics of industrial by-products in determining SCC performance.

Practical implications: FA demonstrated a more favourable balance between workability and later-age mechanical performance than CCW. Its use as a partial cement replacement could reduce Portland cement consumption while maintaining desirable SCC performance. Higher CCW replacement levels may require further mixture optimisation because of their adverse effects on flowability and passing ability.

Originality/value: This study provides a comparative assessment of FA and CCW as partial cement replacements in SCC by relating their chemical characteristics to fresh-state and mechanical performance. The findings provide practical evidence for the valorisation of industrial by-products and support more resource-efficient SCC production.

Keywords: Self-Compacting Concrete; Fly Ash; Calcium Carbide Waste; XRF; Slump Flow; L-Box; Compressive Strength; Tensile Strength; Supplementary Cementitious Materials.

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1.0 INTRODUCTION

Reducing Portland cement clinker demand is essential for lowering the environmental footprint of concrete (Juenger *et al.*, 2019). While supplementary cementitious materials (SCMs) help achieve this, conventional sources face supply constraints. Self-compacting concrete (SCC) offers a sustainable alternative by flowing under its own weight without mechanical vibration, provided it maintains an optimal balance of filling ability, passing ability, viscosity, and segregation resistance (Okamura and Ouchi, 2003; European Project Group, 2005). Incorporating mineral additions into SCC directly impacts its rheological stability and hardened performance.

Fly ash (FA) is a well-established mineral addition that enhances workability and later-age strength, though its efficiency depends on factors like reactivity, glassy phase, and particle characteristics (Xu *et al.*, 2021; Nayak *et al.*, 2022). Similarly, calcium carbide waste (CCW) a calcium-rich industrial by-product from acetylene production shows promise as an alternative binder when combined with reactive siliceous materials (Makaratat *et al.*, 2010; Bawab *et al.*, 2025).

Combining FA and CCW leverages their complementary chemistries: CCW supplies calcium and alkalinity to activate reactions, while FA provides reactive SiO_2 and Al_2O_3 aluminosilicate components (Sun *et al.*, 2015; Makaratat *et al.*, 2010). Despite previous insights into FA–CCW binary binders, the specific impacts of their combined incorporation on SCC fresh-state requirements (such as flowability and passing ability) and mechanical strength development remain underexplored. To bridge this research gap, this study systematically investigates the relationship among binder chemistry, fresh-state properties, and mechanical strength in SCC containing combined FA and CCW additions. The experimental program evaluates optimal replacement levels that successfully balance workability with compressive and tensile strength.

1.1. Fly Ash and Calcium Carbide Waste in Cementitious Systems

Fly ash (FA) is a widely used supplementary cementitious material that modifies fresh and hardened concrete properties depending on factors such as composition, fineness, and reactivity (Xu *et al.*, 2021; Nayak *et al.*, 2022). In self-compacting concrete (SCC), FA enhances flowability and later-age strength, though its content must balance both fresh-state and mechanical responses (Gnanaraj *et al.*, 2021; Singh *et al.*, 2019). Conversely, calcium carbide waste (CCW), or calcium carbide residue (CCR), is a calcium-rich acetylene by-product providing an alkaline environment to support pozzolanic reactions. While FA supplies reactive aluminosilicates, CCW offers necessary calcium phases. Early research established the feasibility of FA–CCR systems (Makaratat *et al.*, 2011), with recent evidence confirming that residue performance depends heavily on fineness, dosage, preparation, and material interactions (Bawab *et al.*, 2025; Mahmmod & Abbas, 2026). Combining FA and CCW leverages these complementary chemistries (silica/alumina versus calcium/alkalinity). However, their combined impact on hydration, particle packing, water demand, and strength cannot be directly deduced from their individual behaviors (Makaratat *et al.*, 2011; Bawab *et al.*, 2025).

1.2. FA–CCW Systems in Self-Compacting Concrete

SCC imposes strict demands regarding filling ability, passing ability, viscosity, and segregation resistance, meaning binder suitability cannot be assessed through compressive strength alone (Jain *et al.*, 2021; Singh *et al.*, 2019). Although the individual and baseline potentials of FA and CCW are recognized, data remains limited regarding their integrated relationship with SCC fresh-state performance, as well as compressive and tensile strength across different replacement levels. Increasing combined replacement reduces cement demand and alters flow behavior, but it can simultaneously affect strength development. This study addresses this gap by systematically evaluating FA–CCW incorporation in SCC. It explores how binder chemistry influences the balance between self-compactability and mechanical performance to establish an optimal replacement range.

2. MATERIALS AND EXPERIMENTAL PROGRAMME

The materials, mix proportions, specimen preparation procedures, and experimental methods adopted in this study were systematically selected to establish the relationships between the constituent materials, fresh-state behaviour, mechanical performance, and chemical characteristics of the investigated mixtures.

2.1. Experimental scope

The supplied experimental programme comprises 11 SCC mixtures. A control mixture containing 100% Portland cement was compared with two independent replacement series:

- i. PC replaced by FA at 5, 10, 15, 20 and 25%; and
- ii. PC replaced by CCW at 5, 10, 15, 20 and 25%.

Thus, the FA and CCW mixtures should be understood as separate replacement series, rather than ternary mixtures containing both FA and CCW simultaneously.

The reported experimental measurements comprised:

- i. XRF chemical characterization of PC, FA and CCW;
- ii. Slump-flow measurement;
- iii. L-box passing-ability measurement;
- iv. Compressive strength at 14, 28 and 56 days; and
- v. Tensile strength at 28 and 56 days.

2.2. Mix Design

Based on EFNARC (2002) recommendations, the mix design for SCC aimed to provide self-compacting concrete with the best possible workability, stability, and strength. A number of experimental combinations were made, gradually increasing the amount of cement replaced with fly ash and CCW. Control specimens without SCMs and SCC specimens with fly ash and CCW replacing OPC by 5%, 10%, 15%, 20%, and 25%, respectively, were added in the mixes.

Table 1: Mix Proportion

S/N	Mix ID	Types of Paste	Total Binder kg/m ³	PC kg/m ³	FA Kg/m ³	CCW Kg/m ³	Fine Agg. Kg/m ³	Coarse Agg. Kg/m ³	Water Kg/m ³	SP g	W/B Ratio
1	SCC	Control	470	460	0	0	883	553	160	4.45	0.4
2	95% PC + 5% FA	Binary	470	446.5	23.5	0	883	553	160	4.45	0.4
3	90% PC + 10% FA	Binary	470	423	47	0	883	553	160	4.45	0.4
4	85%PC+15% FA	Binary	470	399.5	70.5	0	883	553	160	4.45	0.4
5	80%PC+20% FA	Binary	470	376	94	0	883	553	160	4.45	0.4
6	75%PC+25% FA	Binary	470	352.5	117.5	0	883	553	160	4.45	0.4
7	95%PC+5% CCW	Binary	470	446.5	0	23.5	883	553	160	4.45	0.4
8	90% PC + 10% CCW	Binary	470	423	0	47	883	553	160	4.45	0.4
9	85% PC + 15% CCW	Binary	470	399.5	0	70.5	883	553	160	4.45	0.4

10	80% PC + 20% CCW	Binary	470	376	0	94	883	553	160	4.45	0.4
11	75% PC + 25% CCW	Binary	470	352.5	0	117.5	883	553	160	4.45	0.4

Eleven self-compacting concrete (SCC) mixtures were batched at 20 ± 2 °C following EFNARC (2002) guidelines. Dry materials (aggregates, cement, and fly ash or calcined clay waste fractions) were homogenized for 2 minutes. Eighty percent of the mixing water was added, followed by the remaining water pre-blended with a superplasticizer. After 3 minutes of wet mixing and a 1-minute rest, fresh-state properties were evaluated using slump-flow (ASTM C1611) and L-box (BS EN 12350-10) tests. Without mechanical vibration, the SCC mixtures were poured into 100 mm cube and 100 mm $\times$ 200 mm cylinder molds in a single lift. Specimens were covered with damp burlap and polyethylene for 24 hours, then demolded and cured in water at 20 ± 2 °C with >95% relative humidity until testing. Nine cylindrical specimens per batch were prepared for hardened testing. Mechanical properties were assessed using a 2000 kN universal testing machine. Compressive strength was tested at 14, 28, and 56 days (ASTM C39 / BS EN 12390-3) at 0.25 MPa/s. Splitting tensile strength was measured at 28 and 56 days (ASTM C496 / BS EN 12390-6) at 0.03 MPa/s. Each reported value is the average of three identical specimens.

2.3. XRF characterization

The oxide composition of PC, FA and CCW was determined by XRF. The principal chemical constituents and the combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content are presented in Table 2.

ASTM C311 recognizes chemical analysis as an important means of describing the composition and uniformity of fly ash, but explicitly notes that chemical composition alone does not predict concrete performance (ASTM, C311/C311M).

Table 2. XRF chemical composition of binder materials

Oxide	PC (%)	FA (%)	CCW (%)
SiO_2	25.64	59.04	2.69
Al_2O_3	5.24	34.08	0.50
Fe_2O_3	7.15	2.00	0.17
CaO	64.00	0.22	64.00
MgO	0.41	0.43	0.80
SO_3	0.11	0.05	0.31
K_2O	0.05	0.76	0.47
Na_2O	0.31	0.50	0.00
M_2O_5	0.04	0.00	0.00
P_2O_5	0.03	1.11	0.00
LOI	0.67	2.39	31.07
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	38.03	95.12	3.36

The FA result is chemically consistent with a highly aluminosiliceous material: its combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content is 95.12%. ASTM C618 specifies minimum combined oxide requirements for fly ash, together with limits for SO_3 and LOI. However, full conformity cannot be established from the present XRF data alone because ASTM C618 also includes physical and performance requirements such as fineness, strength activity index and water requirement.

3.0. FRESH-STATE PROPERTIES

Slump flow provides an indication of the unconfined flowability of SCC, while the L-box test assesses its ability to pass through restricted openings. These properties are fundamental to SCC because adequate flowability must be accompanied by sufficient passing ability to permit concrete to move through congested reinforcement without blockage.

Table 3. Fresh-state properties of SCC

Mix ID	Binder composition	Slump flow (mm)	L-box ratio
SCC	100% PC	610	0.81
PC-FA5	95% PC + 5% FA	690	0.92
PC-FA10	90% PC + 10% FA	710	0.94
PC-FA15	85% PC + 15% FA	730	0.96
PC-FA20	80% PC + 20% FA	750	0.98
PC-FA25	75% PC + 25% FA	770	1.00
PC-CCW5	95% PC + 5% CCW	680	0.90
PC-CCW10	90% PC + 10% CCW	670	0.88
PC-CCW15	85% PC + 15% CCW	660	0.85
PC-CCW20	80% PC + 20% CCW	650	0.83
PC-CCW25	75% PC + 25% CCW	640	0.80

3.1. Discussion of fresh-state behaviour

Fly ash (FA) and calcium carbide waste (CCW) exerted contrasting effects on self-compacting concrete (SCC) flowability. Increasing FA from 5% to 25% raised the slump flow from 690 to 770 mm and the L-box ratio from 0.92 to 1.00, improving both spread and passing ability. This aligns with findings that spherical fly ash particles reduce interparticle friction (Nayak *et al.*, 2022; Xu *et al.*, 2021). Conversely, increasing CCW from 5% to 25% reduced slump flow from 680 to 640 mm and the L-box ratio from 0.90 to 0.80 due to increased internal friction from coarser particles. Based on EN 206 slump flow classes (SF1: 550–650 mm, SF2: 660–750 mm, SF3: 760–850 mm), the control mixture sits in SF1, FA5–FA15 and CCW5–CCW15 fall in SF2, FA20 reaches upper SF2, FA25 reaches SF3, and CCW25 stays in SF1. While FA progressively advanced mixtures to higher flowability classes, CCW shifted them toward the lower end of the SCC range. Furthermore, all mixtures achieved an L-box ratio of at least 0.80, meeting the general passing-ability threshold defined by European Guidelines.

4.0 HARDENED PROPERTIES

The hardened properties of the investigated mixtures were evaluated to determine the influence of the constituent materials and mix composition on their mechanical performance, with particular emphasis on compressive and tensile strength.

4.1. Compressive strength

The compressive strength results were used to evaluate the load-bearing capacity and strength development of the investigated mixtures and to determine the effect of the different material compositions on the hardened matrix. The measured compressive strength values and their corresponding development across the investigated mixtures are presented in Table 4, as shown in the results below:

Table 4. Compressive strength at 14, 28 and 56 days

Mix ID	Binder composition	14 days (MPa)	28 days (MPa)	56 days (MPa)
SCC	100% PC	23.5	38.0	40.0
PC-FA5	95% PC + 5% FA	22.5	26.5	44.0
PC-FA10	90% PC + 10% FA	21.5	26.0	44.0
PC-FA15	85% PC + 15% FA	20.0	25.5	43.0
PC-FA20	80% PC + 20% FA	19.0	24.5	42.0
PC-FA25	75% PC + 25% FA	18.0	24.0	41.5
PC-CCW5	95% PC + 5% CCW	21.5	26.0	42.0
PC-CCW10	90% PC + 10% CCW	20.5	25.5	41.5
PC-CCW15	85% PC + 15% CCW	20.0	25.0	40.5
PC-CCW20	80% PC + 20% CCW	19.0	24.0	40.0
PC-CCW25	75% PC + 25% CCW	18.0	23.0	38.0

Compressive strength varied significantly with age and replacement type. At 14 and 28 days, the control SCC achieved the highest strength (23.5 MPa and 38.0 MPa, respectively), while all replacement mixtures exhibited strength penalties that increased with replacement levels. By 56 days, a major reversal occurred. Fly ash (FA) mixtures showed strong recovery, with PC-FA5 and PC-FA10 reaching 44.0 MPa (surpassing the control by 10%), and PC-FA25 reaching 41.5 MPa. This late-age gain reflects matrix refinement from reactive fly ash (Fraay *et al.*, 1989; Xu *et al.*, 2021). Although XRF analysis revealed a high combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content (95.12%), bulk chemistry alone does not prove pozzolanic reactivity, as amorphous content varies (Xu *et al.*, 2021). Conversely, the calcium carbide waste (CCW) series showed decreasing 56-day strength as replacement levels increased, dropping from 42.0 MPa at 5% to 38.0 MPa at 25%. This aligns with its high CaO but low aluminosilicate content. While CCW provides a calcium-rich environment, its effectiveness relies on an available reactive siliceous source (Sun *et al.*, 2015; Makaratat *et al.*, 2010). Overall, FA delivered more favourable long-term strength recovery, whereas higher CCW replacement progressively reduced compressive strength.

4.2. Tensile Strength

The tensile strength results were assessed to further characterise the mechanical behaviour and resistance of the hardened mixtures to tensile-induced cracking. The results presented in Table 5 show the variation in tensile strength among the investigated mixtures and provide complementary evidence for interpreting the trends observed in the compressive strength results.

Table 5. Tensile strength at 28 and 56 days

Mix ID	Binder composition	28 days (MPa)	56 days (MPa)
SCC	100% PC	6.20	6.62
PC-FA5	95% PC + 5% FA	5.789	6.005
PC-FA10	90% PC + 10% FA	6.002	6.300
PC-FA15	85% PC + 15% FA	6.980	8.540
PC-FA20	80% PC + 20% FA	4.982	5.635
PC-FA25	75% PC + 25% FA	4.011	4.380
PC-CCW5	95% PC + 5% CCW	4.321	4.980
PC-CCW10	90% PC + 10% CCW	4.653	4.865
PC-CCW15	85% PC + 15% CCW	6.231	6.820

Mix ID	Binder composition	28 days (MPa)	56 days (MPa)
PC-CCW20	80% PC + 20% CCW	5.768	6.270
PC-CCW25	75% PC + 25% CCW	7.545	7.730

Tensile-strength trends differed from compressive results, proving that optimum replacement levels cannot rely on compressive strength alone. Within the fly ash (FA) series at 28 days, tensile strength rose from 5.789 MPa at 5% FA to a peak of 6.980 MPa at 15% FA. By 56 days, the 15% FA mixture reached 8.540 MPa the highest tensile response in the entire dataset. However, strength declined sharply above 15%, dropping to 4.380 MPa at 25% FA. This strong 56-day performance at 15% replacement reflects progressive matrix refinement from FA's reactive aluminosilicate fraction (Nayak *et al.*, 2022).

Conversely, the calcium carbide waste (CCW) series exhibited a distinct tensile response. While 5% and 10% replacements lagged behind the control, 56-day values rose at higher levels, reaching 6.820 MPa at 15% and 6.270 MPa at 20%. Notably, the 25% CCW mixture achieved 7.730 MPa at 56 days, outperforming both the control and all other CCW mixtures. Unlike FA, CCW behaves differently due to its high CaO content and low reactive-oxide levels. Rather than acting as a standard pozzolan, CCW supplies calcium and alkalinity to facilitate cementitious reactions when reactive materials are present (Sun *et al.*, 2015; Makaratat *et al.*, 2010).

4.3. Integrated Discussion: Relationship Between Chemistry, Fresh Behaviour and Strength

The principal scientific value of the dataset lies in the fact that the XRF, fresh-state and hardened-state results show systematic differences between FA and CCW.

Table 6. Integrated interpretation of the experimental results

Characteristic	FA series	CCW series
Dominant chemical feature	SiO ₂ - and Al ₂ O ₃ -rich	CaO-rich
SiO ₂ (%)	59.04	2.69
Al ₂ O ₃ (%)	34.08	0.50
CaO (%)	0.22	64.00
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (%)	95.12	3.36
LOI (%)	2.39	31.07
Slump-flow response	Increases with replacement	Decreases with replacement
L-box response	Increases with replacement	Decreases with replacement
Best 56-day compressive strength	44.0 MPa at 5–10% FA	42.0 MPa at 5% CCW
Best 56-day tensile strength	8.54 MPa at 15% FA	7.73 MPa at 25% CCW
Overall response	Strong fresh-state and later-age performance	Reduced flowability but competitive high-level tensile response

The chemical composition provides a logical starting point for understanding these differences. FA has a combined reactive-oxide content of 95.12%, compared with only 3.36% for CCW. The former is characteristic of a strongly aluminosilicate-rich material, while the latter is dominated by calcium. This distinction is important because SCM performance depends not only on the amount of replacement but also on the chemistry, mineralogy, particle characteristics and reactivity of the material (Juenger *et al.*, 2019; Xu *et al.*, 2021).

The fresh-state results reinforce this distinction. Increasing FA content simultaneously increased slump flow and L-box ratio. This means that the FA series did not merely become more fluid; it also retained

improved passing ability. This is desirable for SCC because high flowability without adequate passing ability would not necessarily translate into satisfactory placement. The European Guidelines identify filling and passing ability as fundamental properties of SCC. CCW produced the opposite fresh-state response. Increasing its replacement level caused progressive reductions in both flow measures. This finding is particularly important for practical application because the mixture with the highest CCW tensile strength, PC–CCW25, also had the lowest slump flow and L-box ratio in the CCW series. Consequently, selecting the 25% CCW mixture solely on the basis of tensile strength would overlook its less favourable fresh-state performance.

A similar trade-off appears in the FA series. PC–FA25 had the highest slump flow and L-box ratio, but it did not provide the highest tensile strength. The maximum tensile performance occurred at 15% FA, while maximum compressive strength occurred at 5–10% FA. Therefore, there is no single replacement percentage that simultaneously maximizes every measured property. This is a key finding for SCC mixture optimization. A technically meaningful optimum should be defined according to the intended application and the relative importance of fresh and hardened properties rather than by selecting the maximum value from a single test.

4.4. Comparison of Compressive and Tensile Strength Development

Comparing compressive and tensile strength reveals distinct mechanical behaviours. Between 28 and 56 days, the control SCC's compressive strength rose from 38.0 to 40.0 MPa, and its tensile strength increased from 6.20 to 6.62 MPa. Moderate fly ash replacement yielded substantial relative tensile gains, notably in the PC–FA15 mixture, which grew from 6.98 to 8.54 MPa while its compressive strength increased from 25.5 to 43.0 MPa, reflecting continued internal matrix refinement during later curing.

In contrast, the 25% CCW mixture demonstrated an intriguing divergence. At 56 days, its compressive strength dropped slightly relative to the control to 38.0 MPa, yet its tensile strength reached 7.73 MPa. This indicates that its tensile response was significantly stronger than what would be predicted from compression tests alone. Such distinctions highlight why waste-derived binder systems cannot be accurately assessed through a single mechanical property. Aligning with European SCC guidelines, compressive and tensile strengths must be treated as independent engineering properties rather than interchangeable performance measures (European Project Group, 2005).

5.0 SUSTAINABILITY AND PRACTICAL IMPLICATIONS

The use of industrial by-products in concrete has potential environmental benefits because partial cement replacement can reduce the demand for Portland cement while providing productive applications for materials that might otherwise require disposal. Reviews of waste-derived cement additions have identified waste utilization and cement reduction as important pathways towards more resource-efficient concrete production (Paris *et al.*, 2016; Juenger *et al.*, 2019). The present results indicate that FA provides a particularly attractive balance for SCC. Its increasing replacement level improved the measured fresh-state properties, while moderate replacement generated substantial later-age tensile performance and low-to-moderate replacement produced the highest 56-day compressive strength.

CCW also demonstrated useful mechanical performance, particularly in tensile strength at 25% replacement. However, its high LOI of 31.07% and progressively decreasing flowability indicate that greater attention would be required to its processing, physical characteristics and mixture compatibility. Recent reviews emphasize that calcium carbide residue performance is strongly affected by preprocessing, fineness and dosage, and that higher replacement levels may require complementary pozzolanic materials to achieve balanced performance (Bawab *et al.*, 2025).

6.0 CONCLUSION

Based on the supplied experimental dataset, the following conclusions can be drawn:

- i. The FA and CCW materials possess fundamentally different chemical compositions. FA contains 59.04% SiO₂, 34.08% Al₂O₃ and 95.12% combined SiO₂ + Al₂O₃ + Fe₂O₃, whereas CCW contains 64.00% CaO and only 3.36% combined SiO₂ + Al₂O₃ + Fe₂O₃.
- ii. FA substantially improved the fresh-state performance of SCC. Increasing FA from 5 to 25% increased slump flow from 690 to 770 mm and the L-box ratio from 0.92 to 1.00.
- iii. CCW produced the opposite fresh-state trend. Increasing CCW from 5 to 25% reduced slump flow from 680 to 640 mm and the L-box ratio from 0.90 to 0.80.
- iv. Replacement mixtures showed delayed early-age compressive strength development. At 14 and 28 days, the control SCC generally exceeded the modified mixtures.
- v. FA produced strong later-age compressive-strength recovery. Based on the supplied numerical dataset, PC-FA5 and PC-FA10 achieved 44.0 MPa at 56 days, compared with 40.0 MPa for the control.
- vi. The optimum FA level depended on the mechanical property considered. The highest 56-day compressive strength occurred at 5–10% FA, whereas the highest tensile strength occurred at 15% FA, reaching 8.54 MPa.
- vii. CCW exhibited a different mechanical response. Its 56-day compressive strength decreased progressively with increasing replacement, but 25% CCW produced the highest tensile strength within the CCW series, reaching 7.73 MPa.
- viii. No single replacement level maximized all properties. FA25 provided the highest fresh-state flowability, FA5–10 provided the highest compressive strength, and FA15 provided the highest tensile strength. For CCW, the highest tensile strength occurred at 25%, although this mixture had the least favourable fresh-state performance.
- ix. The results support FA as the more balanced replacement material for SCC under the measured conditions, particularly where fresh-state performance and later-age mechanical strength are jointly considered.

CCW remains promising but requires more comprehensive characterization. Its high CaO content and competitive tensile performance warrant further investigation, particularly with respect to particle characteristics, mineralogy, hydration, durability and optimum processing.

7.0 RECOMMENDATIONS

Based on the findings of the present study, the following areas are required for further research;

- i. Density, air content and segregation resistance;
- ii. Sem/eds to investigate matrix development;
- iii. Thermogravimetric analysis to examine hydration;
- iv. Water absorption and sorptivity;
- v. Chloride penetration;
- vi. Sulfate resistance;
- vii. Carbonation;
- viii. Drying/autogenous shrinkage;
- ix. Replicate results with standard deviation;
- x. Statistical significance testing; and
- xi. Life-cycle/environmental assessment.

These additions would allow the study to move from a performance-based experimental paper towards a stronger mechanism-based materials-science paper, which is generally more competitive for high-impact cement and concrete journals.

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