Performance Assessment of Sustainable Self-Compacting Concrete Incorporating GBFS, CPA, and CSA as Cement Replacement Materials

Adeniji A.A., and Ayegbusi O.A.

Department of Civil Engineering, University of Ibadan, Ibadan, Nigeria

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INTRODUCTION

Self-Compacting Concrete (SCC) has become an important advancement in concrete technology due to its ability to flow under its own weight, fill formwork completely, and pass through congested reinforcement without external vibration. These characteristics improve construction efficiency, reduce labor and noise, and enhance surface finish and structural reliability (Okamura & Ouchi, 2003; EFNARC, 2005). As a result, SCC is increasingly used in complex structural applications. However, the production of SCC often requires high cement content and carefully controlled aggregate grading, which can increase cost and environmental impact. In recent years, growing concerns over climate change and resource depletion have driven research toward more sustainable concrete materials. One widely adopted approach is the use of supplementary cementitious materials (SCMs) to partially replace ordinary Portland cement. Ground Granulated Blast Furnace Slag (GBFS), a by-product of the steel industry, has been extensively studied due to its ability to reduce carbon emissions while improving long-term mechanical performance and durability of concrete (Shi et al., 2015; Thomas, 2018). Studies conducted between 2020 and 2025 have confirmed that GBFS can enhance later-age compressive strength in SCC by refining pore structure and contributing to continued hydration, although early-age strength may be slightly reduced depending on replacement level (Singh et al., 2021; Li & Huang, 2023). In addition to cement replacement, the selection and proportioning of aggregates play a critical role in determining SCC performance. Aggregate characteristics such as shape, surface texture, and grading strongly influence fresh properties, particularly flowability, passing ability, and segregation resistance (Neville, 2011). Recent research has shown that the use of alternative or processed aggregates, including Crushed Stone Aggregate (CSA) and Coarse Processed Aggregate (CPA), can significantly affect SCC rheology and strength development. Angular and rough-textured aggregates tend to increase internal friction, thereby reducing workability unless compensated by mix design adjustments or chemical admixtures (Mohammadhosseini et al., 2021; Wang et al., 2022). Workability has consistently been identified as one of the most sensitive properties of SCC incorporating sustainable materials. Several studies conducted in the last five years report that increasing the proportion of SCMs or alternative aggregates can reduce slump flow and stability if not properly optimized (Abbas et al., 2023; Safiuddin et al., 2021). Conversely, appropriate use of GBFS has been shown to improve the viscosity and cohesiveness of SCC, contributing to stable flow behavior when combined with suitable aggregate grading (Zhang et al., 2022).

Compressive strength remains a key performance indicator for structural SCC. Recent studies indicate that SCC containing GBFS generally exhibits satisfactory or enhanced compressive strength at 28 days due to latent hydraulic reactions, while the type and quality of coarse aggregate significantly influence strength development at all curing ages (Jindal & Paliwal, 2022; Thomas et al., 2021). However, the combined influence of GBFS with different coarse aggregate types on both fresh and hardened properties has not been sufficiently addressed in a single experimental framework. Many existing studies focus either on workability or on compressive strength alone, or examine materials independently rather than in combination, leading to fragmented conclusions. This lack of integrated understanding presents a practical challenge for engineers and researchers seeking to design sustainable SCC mixtures that balance flowability with adequate strength. In particular, there is limited clarity on how varying percentages of GBFS, CPA, and CSA simultaneously affect workability and compressive strength development at different curing ages. Therefore, this study aims to assess

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the performance of sustainable self-compacting concrete incorporating varying percentages of GBFS, CPA, and CSA. The workability of the SCC mixes is evaluated to determine their suitability for self-compaction, while the compressive strength of concrete cubes is determined at curing ages of 7, 14, and 28 days. The findings are expected to contribute to optimized SCC mix designs that support sustainability without compromising structural performance.

MATERIALS AND METHOD

Materials

Ordinary Portland Cement (OPC) conforming to ASTM C150 / IS 269 / BS EN 197-1 was used as the primary binder in this study. Ground Granulated Blast Furnace Slag (GBFS), CPA, and CSA were incorporated as supplementary cementitious materials and used as partial replacements for cement. The total binder content was maintained at 100 kg/m³ for all mixes, while the replacement levels of GBFS, CPA, and CSA were varied equally. The water-to-binder ratio was kept constant at 0.40, and a polycarboxylate-based superplasticizer was used to achieve the required self-compacting characteristics Natural river sand conforming to ASTM C33 / IS 383 was used as fine aggregate. Two types of coarse aggregates—Crushed Stone Aggregate (CSA) and Coarse Processed Aggregate (CPA)—were used in the concrete mixes. The coarse aggregates were tested for particle size distribution, specific gravity, and water absorption following ASTM C127 / IS 2386 (Part III), while sieve analysis was carried out in accordance with ASTM C136 / IS 2386 (Part I). Potable water suitable for concrete mixing and curing was used, complying with ASTM C1602. A polycarboxylate ether-based high-range water-reducing admixture (superplasticizer) compatible with SCC was incorporated to achieve the required flowability. The admixture conformed to ASTM C494 Type F.

Mix Proportions

Self-compacting concrete mixes were prepared with varying percentages of GBFS as a partial replacement of cement and different combinations of CSA and CPA as coarse aggregates. A control mix without GBFS was prepared for comparison. The water-to-binder ratio was maintained constant across all mixes to isolate the effects of GBFS and aggregate variation. Mix proportions were designed in accordance with the EFNARC (2005) guidelines for Self-Compacting Concrete, ensuring that the mixes satisfied the requirements for flowability, passing ability, and segregation resistance. The dosage of superplasticizer was adjusted as required to achieve SCC performance criteria.

Mixing Procedure

Concrete mixing was carried out using a laboratory pan mixer. Initially, cement, GBFS, fine aggregate, and coarse aggregates were dry-mixed for approximately 1–2 minutes to ensure uniform distribution. Subsequently, mixing water combined with the required dosage of superplasticizer was added gradually, and mixing continued until a homogeneous and self-compacting concrete mix was obtained.

Workability Testing

The workability of fresh SCC was evaluated immediately after mixing using SCC-specific tests recommended by EFNARC. Slump flow diameter was measured to assess flowability in accordance with ASTM C1611 / EFNARC (2005). Visual observations were made to ensure uniform flow and absence of segregation or bleeding.

Casting and Curing of Specimens

Concrete specimens were cast in standard cube molds for compressive strength testing. Due to the self-compacting nature of the concrete, no mechanical vibration was applied during casting. After casting, specimens were covered to prevent moisture loss and stored at room temperature for 24 hours. The specimens were then demolded and cured in water in accordance with ASTM C511 until the designated testing ages.

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Compressive Strength Testing

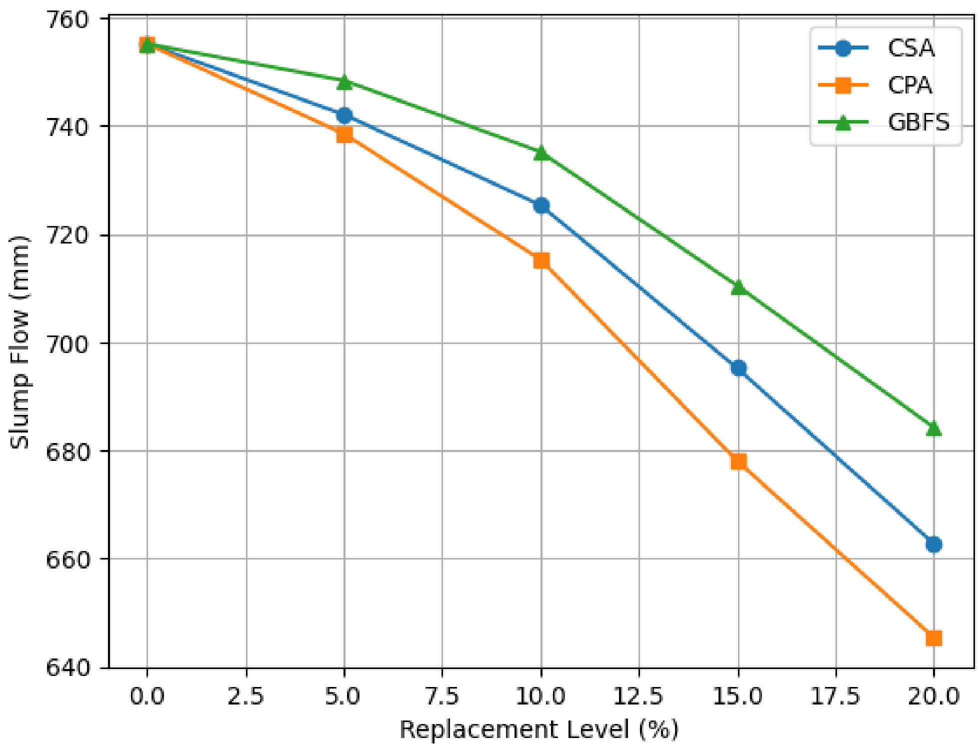
Compressive strength tests were conducted on concrete cube specimens at curing ages of 7, 14, and 28 days. Testing was performed using a calibrated compression testing machine following ASTM C39 / IS 516 / BS EN 12390-3. For each mix and curing age, at least three specimens were tested, and the average compressive strength value was reported.

RESULTS AND DISCUSSIONS

Workability

Table 1: Slump Values of CSA, CPA and GBFS at different replacement levels

Replacement Level (%)	CSA	CPA	GBFS
0% (Control)	755.0	755.0	755.0
5%	742.10	738.55	748.40
10%	725.35	715.30	735.20
15%	695.15	678.15	710.45
20%	662.70	645.40	684.25



Graph 1: Graph showing the slump values of CSA, CPA and GBFS at different replacement levels

The slump flow results of the self-compacting concrete (SCC) incorporating CSA, CPA, and GBFS as partial cement replacements are presented in Table X. The control mix (0% replacement) achieved a slump flow diameter of 755.20 mm, confirming adequate filling ability and compliance with SCC workability requirements as specified in EFNARC guidelines. A consistent reduction in slump flow was observed with increasing replacement levels for all three materials. At 5% replacement, the reduction was relatively small, indicating that low replacement levels had a limited impact on the flowability of SCC. However, as the replacement level increased to 10–20%, a more pronounced decrease in slump flow was recorded. Among the three materials, CSA showed the greatest reduction in slump flow, decreasing from 755.20 mm (control) to 662.80 mm at 20% replacement. This behavior can be attributed to the finer particle size and higher surface area of CSA, which increases water demand and internal friction within the fresh mix. Similar reductions in SCC workability due to fine cementitious additives have been reported by Okamura and Ouchi (2003) and

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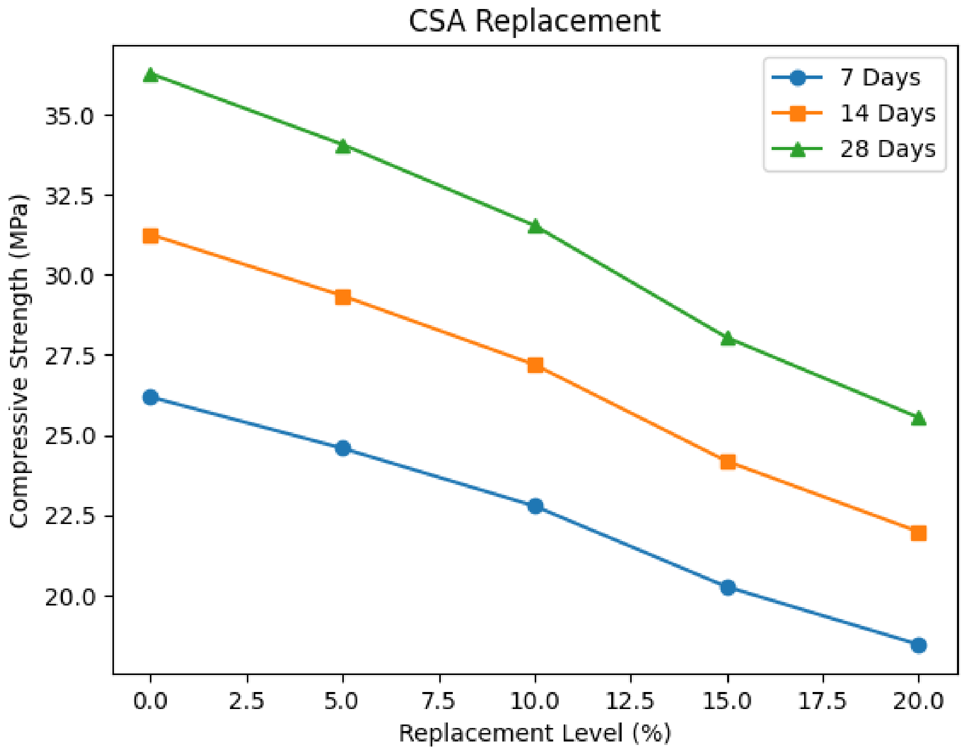
Khayat (2020), who noted that increased powder content can adversely affect flow if not accompanied by mix adjustments. Concrete containing CPA exhibited the most significant loss of workability, with slump flow reducing to 645.45 mm at 20% replacement. The sharper decline suggests that CPA particles likely possess higher angularity or irregular texture, leading to greater inter-particle resistance and reduced lubrication in the paste phase. Previous studies have shown that cement replacement materials with rough surfaces or porous structures can substantially reduce SCC flowability (Nepomuceno et al., 2021). In contrast, GBFS-based SCC demonstrated comparatively better workability retention, maintaining a slump flow of 684.30 mm at 20% replacement. The relatively higher slump values observed for GBFS mixes can be attributed to the smooth, glassy texture and latent hydraulic nature of GBFS particles, which enhance particle packing and reduce friction within the fresh concrete. This finding aligns with earlier studies reporting improved or more stable workability in SCC containing GBFS due to its favorable morphology and particle shape (Shi et al., 2021; Zhang et al., 2022). Overall, although slump flow decreased with increasing replacement levels for CSA, CPA, and GBFS, all mixes up to 20% replacement remained within acceptable SCC flow ranges, indicating satisfactory fresh concrete performance. The results suggest that GBFS is more compatible with SCC in terms of workability, while CSA and CPA require careful control of replacement levels or mix design modifications—such as superplasticizer dosage adjustment—to maintain optimal flow characteristics. These findings confirm that partial replacement of cement with supplementary materials influences the rheological behavior of SCC and highlight the importance of balancing sustainability objectives with fresh concrete performance requirements.

Compressive Strength

Table 2: Compressive strength of CSA,CPA and GBFS at different replacement levels and ages

Replacement (%)	CSA 7days	CSA 14days	CSA 28days	CPA 7days	CPA 14days	CPA 28days	GBFS 7days	GBFS 14days	GBFS 28days
0	26.18	31.25	36.27	26.18	31.18	36.24	26.09	31.17	36.32
5	24.58	29.34	34.06	23.14	27.56	32.03	25.22	30.12	35.10
10	22.78	27.19	31.53	20.62	24.55	28.52	24.13	28.83	33.60
15	20.26	24.18	28.04	17.38	20.65	24.04	22.33	26.68	31.10
20	18.46	21.98	25.54	15.39	18.28	21.28	20.89	24.96	29.10



Graph 2a: Compressive Strength of CSA

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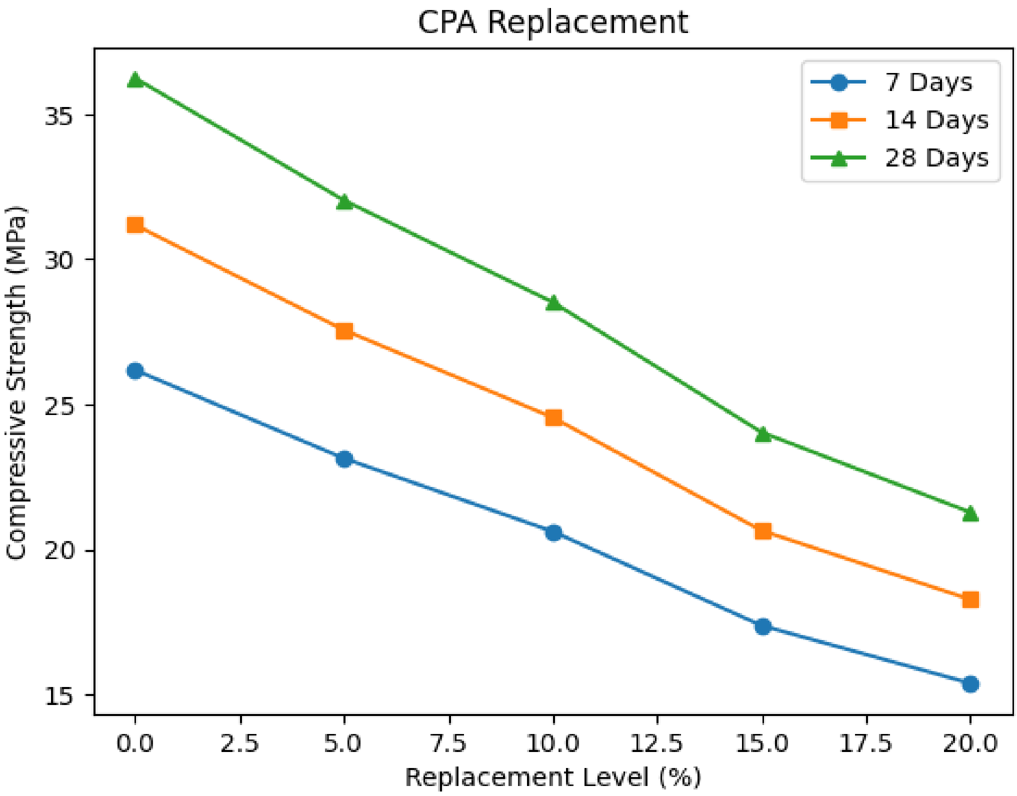
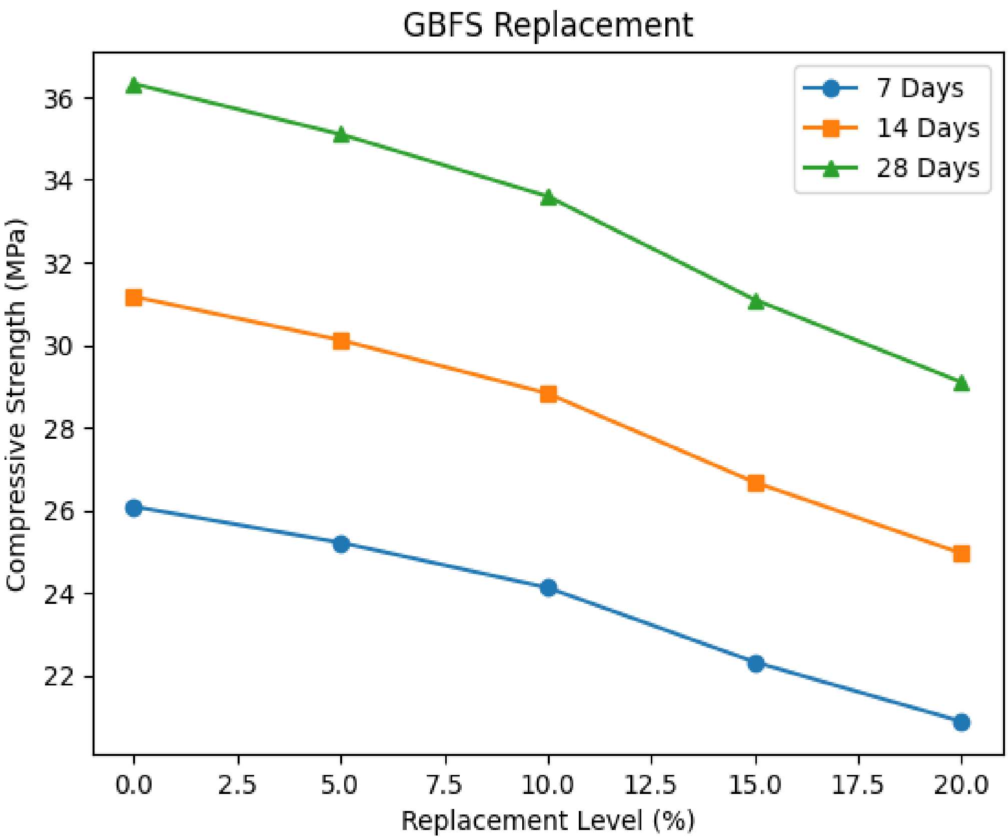


Graph 2b: Compressive Strength of CPA



Graph 2c: Compressive Strength of GBFS

The compressive strength results of self-compacting concrete incorporating CSA, CPA, and GBFS as partial cement replacements at curing ages of 7, 14, and 28 days are illustrated in Figures X–W. The control mix exhibited the highest strength at all ages, confirming the baseline performance of conventional SCC.

Effect of CSA Replacement

The CSA-based SCC showed a gradual reduction in compressive strength with increasing replacement level at all curing ages. At 28 days, strength decreased from 36.27 MPa for the control mix to 25.54 MPa at 20% replacement. This reduction can be attributed to the dilution effect caused by cement replacement and the relatively lower cementitious reactivity of CSA compared to Portland cement. Although CSA may contribute to early hydration, excessive replacement reduces the availability of clinker phases responsible for strength development, particularly at later ages (Neville, 2011; Zhang et al., 2021).

Effect of CPA Replacement

CPA replacement resulted in the most pronounced strength reduction among the three materials. At 20% replacement, the 28-day compressive strength dropped to 21.28 MPa, representing a significant decline compared to the control. This behavior suggests limited pozzolanic or hydraulic activity of CPA, leading to weaker paste structure and reduced load-bearing capacity. Similar findings have been reported in studies where cement replacement materials with low reactivity caused reduced strength due to inadequate formation of calcium silicate hydrate (C–S–H) gel (Scrivener et al., 2018; Li et al., 2020).

Effect of GBFS Replacement

In contrast, GBFS-based SCC demonstrated superior strength retention across all curing ages. At 20% replacement, the 28-day compressive strength remained relatively high at 29.10 MPa. This improved performance is attributed to the latent hydraulic properties of GBFS, which react with calcium hydroxide to form additional C–S–H gel, enhancing matrix densification over time. The strength development trend observed is consistent with previous studies reporting improved long-term strength in SCC incorporating GBFS (Shi et al., 2021; Thomas et al., 2022).

Comparative Performance at 28 Days

The combined 28-day compressive strength comparison clearly shows that GBFS outperformed both CSA and CPA at all replacement levels, followed by CSA, while CPA exhibited the lowest strength values. This trend highlights the importance of material reactivity in cement replacement strategies. While CSA and CPA primarily act as fillers at higher replacement levels, GBFS actively participates in hydration reactions, improving strength development and microstructural integrity.

Overall, the results indicate that cement replacement beyond 10–15% leads to noticeable strength reduction, particularly for CSA and CPA. However, GBFS can be safely used at higher replacement levels with acceptable strength performance, making it more suitable for sustainable SCC applications.

The results demonstrate a clear interaction between the fresh and hardened properties of self-compacting concrete (SCC) incorporating CSA, CPA, and GBFS as partial cement replacements. Slump flow decreased with increasing replacement levels for all materials, reflecting higher water demand and increased internal friction due to finer particle sizes (Khayat, 2020). GBFS mixes exhibited comparatively better flowability, attributed to the smooth, glassy texture of slag particles that improves paste lubrication (Shi et al., 2021). Compressive strength declined with increasing CSA and CPA content at all curing ages due to cement dilution and limited reactivity (Neville, 2011). CPA showed the greatest strength reduction, indicating weak contribution to hydration. In contrast, GBFS mixes maintained higher later-age strength owing to latent hydraulic reactions and continued C–S–H formation (Scrivener et al., 2018). The combined assessment indicates that excessive replacement adversely affects both workability and strength. Replacement levels up to 10–15% are suitable for CSA and CPA, while GBFS can be used up to 20% with acceptable SCC performance (Thomas et al., 2022).

CONCLUSION

This study investigated the effect of partial cement replacement with CSA, CPA, and GBFS on the fresh and hardened properties of self-compacting concrete. The results demonstrate that increasing replacement levels significantly influence both slump flow and compressive strength development.

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Slump flow decreased progressively with increasing replacement levels for all materials, indicating reduced workability due to higher water demand and increased internal friction. Among the materials studied, GBFS exhibited the best workability retention, while CPA showed the greatest reduction in flowability. Compressive strength results revealed a similar trend, with strength decreasing as replacement levels increased. CSA and CPA mixes experienced notable strength reductions due to dilution effects and limited reactivity, whereas GBFS-based mixes maintained relatively higher strength, particularly at 28 days, due to its latent hydraulic properties.

Overall, the study confirms that GBFS is the most suitable cement replacement material for SCC, offering a better balance between workability and compressive strength. Replacement levels of up to 10–15% for CSA and CPA and up to 20% for GBFS can be adopted without severely compromising SCC performance. These findings support the use of GBFS as a sustainable cement replacement material in self-compacting concrete applications.

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