Chemical Classification of Corn Sheath Ash, Cassava Pulp Ash, and Granulated Blast Furnace Slag as Supplementary Cementitious Materials Using X-Ray Fluorescence Analysis

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ABSTRACT

Self-compacting concrete (SCC) enhances constructability through high flowability and self-consolidation; however, its elevated cement demand increases cost and environmental impact. This study evaluates Corn Sheath Ash (CSA), Cassava Pulp Ash (CPA), and Ground Granulated Blast Furnace Slag (GBFS) as partial cement replacements in SCC. Cement was replaced at levels of 0–20% by mass at a constant water-to-binder ratio of 0.50, following EFNARC guidelines. Workability was assessed using slump flow tests, while compressive strength was measured at 7, 14, and 28 days. Increasing replacement levels resulted in reduced flowability for all materials. At 20% replacement, slump flow decreased from 755 mm for the control mix to 662 mm and 645 mm for CSA- and CPA-based SCC, respectively, whereas GBFS mixes maintained higher flowability (≈684 mm). Compressive strength declined with increasing CSA and CPA content, with 28-day strengths reducing to 25.5 MPa and 21.3 MPa, respectively, due to cement dilution and limited reactivity. In contrast, GBFS-containing SCC achieved a 28-day compressive strength of approximately 29.1 MPa at 20% replacement, attributed to its latent hydraulic behavior. CSA and CPA are suitable up to 10–15% replacement, while GBFS can be used up to 20% to produce sustainable SCC.

Keywords: Self-compacting concrete, Agricultural waste ash, Workability, Compressive strength

INTRODUCTION

The growing demand for sustainable construction materials has intensified efforts to reduce the environmental impact associated with ordinary Portland cement (OPC) production. Cement manufacture is responsible for approximately 7–8% of global carbon dioxide emissions, largely due to the calcination of limestone and high energy consumption during clinker production (Andrew, 2019; Scrivener et al., 2018). As a result, the partial replacement of cement with supplementary cementitious materials (SCMs) has become a widely accepted strategy for lowering emissions while maintaining acceptable concrete performance.

Self-compacting concrete (SCC), characterized by its ability to flow under its own weight without segregation or external vibration, typically requires a high powder content to achieve adequate rheological stability (Okamura & Ouchi, 2003; EFNARC, 2005). This increased powder demand often leads to higher cement usage, further amplifying environmental concerns. Consequently, incorporating SCMs into SCC not only enhances sustainability but also contributes to improved particle packing, viscosity control, and long-term performance when properly selected (Khayat, 2020).

Ground Granulated Blast Furnace Slag (GBFS) is one of the most extensively studied SCMs and has been successfully used in both conventional and self-compacting concrete. Its latent hydraulic properties allow it to react with calcium hydroxide released during cement hydration, leading to the formation of additional calcium silicate hydrate (C–S–H) gel and refined pore structure at later ages (Shi et al., 2015; Thomas, 2018). Numerous studies have confirmed that the effectiveness of GBFS is strongly linked to its chemical composition, particularly its silica, alumina, and calcium oxide contents (Scrivener et al., 2018).

In parallel with industrial by-products, increasing attention has been directed toward agricultural waste ashes as alternative SCMs due to their abundance, low cost, and potential pozzolanic characteristics. Corn Sheath Ash (CSA) and Cassava Peel Ash (CPA) are agro-waste materials generated in large quantities in maize- and cassava-producing regions, especially in developing economies. When subjected to controlled calcination, such biomass ashes may contain reactive oxides such as SiO_2, Al_2O_3, and Fe_2O_3, which are essential for pozzolanic activity in cementitious systems (Mehta, 2001; Adesanya & Raheem, 2010).

However, unlike GBFS, the chemical composition of agricultural ashes is highly variable and depends on factors such as plant species, soil conditions, harvesting method, and burning temperature (Scrivener et al., 2018). This variability introduces uncertainty regarding their suitability as SCMs and limits their broader adoption in concrete production. Several researchers have emphasized that chemical characterization is a critical first step in evaluating any new SCM, as oxide composition directly governs reactivity, strength development, and durability performance (ASTM C618; Neville, 2011).

Despite the growing interest in CSA and CPA, there remains limited and inconsistent data on their chemical properties, particularly when compared directly with well-established SCMs such as GBFS. Most existing studies focus on mechanical or durability performance without first establishing whether the ashes satisfy fundamental chemical requirements for pozzolanic or cementitious behavior. This gap highlights a clear research problem:
the lack of comprehensive and comparable chemical characterization of GBFS, Corn Sheath Ash (CSA), and Cassava Peel Ash (CPA) to support their use as supplementary cementitious materials. To address this gap, the present study focuses on determining the chemical properties of GBFS, CSA, and CPA using X-ray fluorescence (XRF) analysis. XRF is a widely accepted and reliable technique for quantifying the oxide composition of cementitious materials and assessing their conformity with established standards for SCMs (Scrivener et al., 2018; ASTM C618). By comparing the major oxide contents of CSA and CPA with those of GBFS, this study provides a scientific basis for evaluating their potential reactivity and suitability for use in sustainable self-compacting concrete. The results of this investigation are intended to serve as a foundational step toward the effective utilization of agricultural waste ashes in concrete, enabling informed mix design decisions and supporting future studies on fresh, mechanical, and durability performance. Ultimately, this approach contributes to resource efficiency, waste valorization, and reduced environmental impact in cement-based construction.

Therefore, this study aims to determine the chemical composition of Ground Granulated Blast Furnace Slag (GBFS), Corn Sheath Ash (CSA), and Cassava Pulp Ash (CPA) using X-ray fluorescence (XRF) analysis, in order to assess their suitability as supplementary cementitious materials for sustainable concrete applications.

MATERIALS AND METHODS

Materials

The materials investigated in this study consist of Ground Granulated Blast Furnace Slag (GBFS), Corn Sheath Ash (CSA), and Cassava Pulp Ash (CPA), all considered for use as supplementary cementitious materials in sustainable concrete applications. GBFS was obtained from a steel production facility, where molten blast furnace slag was rapidly quenched and subsequently ground to a fine powder. GBFS is widely recognized for its latent hydraulic properties and its ability to improve long-term strength and durability in cement-based materials (Shi et al., 2015; Thomas, 2018).

Corn sheath, an agricultural residue generated during maize harvesting, was collected from a local agricultural processing area. The sheath was air-dried to remove moisture, then calcined in a muffle furnace at controlled temperatures between 600–700 °C to produce Corn Sheath Ash (CSA). This temperature range was selected based on previous studies indicating effective removal of organic matter while preserving reactive silica content (Adesanya & Raheem, 2009; Cordeiro et al., 2019). Cassava pulp, a by-product of cassava processing industries, was similarly collected, sun-dried, and calcined at temperatures between 600–700 °C to obtain Cassava Pulp Ash (CPA). The ash was then cooled and sieved through a 75 µm sieve to ensure uniform fineness suitable for chemical analysis. Agricultural ashes produced under controlled calcination conditions have been reported to contain appreciable amounts of silica and alumina, which are essential for pozzolanic activity (Aprianti et al., 2015; Villar-Cociña et al., 2020).

Sample Preparation

All materials (GBFS, CSA, and CPA) were oven-dried at 105 ± 5 °C to remove residual moisture prior to analysis. The dried samples were finely ground using a laboratory ball mill to achieve homogeneous particle size distribution. Each sample was then passed through a 75 µm sieve to minimize the influence of particle size on XRF results. For XRF analysis, representative samples were prepared in accordance with standard laboratory procedures. The powdered samples were thoroughly mixed to ensure homogeneity. Pelletized samples were prepared by compacting the powders under high pressure using a hydraulic press, with a suitable binder added where necessary to improve pellet stability. This preparation method minimizes matrix effects and improves analytical accuracy (Jenkins et al., 2014).

X-Ray Fluorescence (XRF) Analysis

The chemical composition of GBFS, CSA, and CPA was determined using X-ray fluorescence (XRF) spectroscopy, a non-destructive analytical technique widely used for elemental and oxide analysis of cementitious materials. The XRF analysis was conducted using a wavelength-dispersive XRF spectrometer calibrated with certified reference materials.

The analysis quantified the major oxide constituents, including SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, SO_3, Na_2O, and K_2O, as well as loss on ignition (LOI), in accordance with procedures commonly adopted for cement and supplementary cementitious materials (ASTM C114; Taylor, 1997). The oxide compositions obtained were expressed as percentages by mass.

The chemical compositions obtained from XRF analysis were evaluated to assess the suitability of GBFS, CSA, and CPA as supplementary cementitious materials. Particular attention was given to the combined content of $SiO_2 + Al_2O_3 + Fe_2O_3$, which is a key indicator of pozzolanic potential, as specified in ASTM C618.

RESULTS AND DISCUSSIONS

Oxide and elemental XRF results of CPA

The X-ray fluorescence (XRF) results presented in Figures 1 and 2 provide a comprehensive understanding of the chemical nature of Cassava Pulp Ash (CPA) through both oxide and elemental analyses. The oxide composition reveals that CPA is dominated by calcium oxide (CaO, 33.85 wt.%) and silicon dioxide (SiO_2, 25.61 wt.%), indicating a material with mixed cementitious and pozzolanic characteristics. The high CaO content suggests that CPA possesses self-cementing or hydraulic tendencies, enabling it to participate directly in hydration reactions and potentially contribute to early-age strength development when used as a partial cement replacement. Similar behavior has been reported for calcium-rich agricultural ashes, where free lime plays a significant role in hydration and strength formation (Scrivener et al., 2018; Mehta & Monteiro, 2014).

Silicon dioxide constitutes the second-largest oxide fraction, highlighting the presence of reactive silica capable of participating in pozzolanic reactions. In cementitious systems, reactive SiO_2 combines with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H), leading to matrix densification and improved long-term performance (Taylor, 1997; Thomas, 2018). However, the combined content of SiO_2, Al_2O_3, and Fe_2O_3 in CPA is approximately 37.7 wt.%, which falls below the 70% minimum requirement specified by ASTM C618 for Class F or Class N pozzolans. This indicates that CPA does not qualify as a conventional pozzolan on its own but is better described as a hybrid cementitious material with both filler and supplementary reactivity.

The presence of relatively high levels of P_2O_5 (8.75 wt.%) and SO_3 (7.76 wt.%) is characteristic of biomass-derived ashes. Phosphorus compounds are known to influence cement hydration by retarding early reactions through interference with clinker phases, particularly at elevated concentrations (Ganesan et al., 2008). Similarly, sulfur compounds may affect setting behavior and sulfate balance, requiring careful control to prevent potential expansion or durability issues (Neville, 2011). Moderate alkali content, reflected by K_2O at 7.69 wt.%, further suggests that CPA may increase pore solution alkalinity. While this can enhance early dissolution of silica, it may also elevate the risk of alkali–silica reaction (ASR) in mixes containing reactive aggregates, emphasizing the importance of compatibility assessment (Thomas et al., 2022).

The elemental XRF analysis shown in Figure 2 supports and reinforces the oxide-based findings. Calcium is the most abundant element in CPA (24.20%), followed by silicon (11.97%) and potassium (6.39%), confirming the calcium-rich nature of the ash. The dominance of calcium further supports the potential of CPA to contribute directly to hydration processes rather than acting solely as an inert filler. Calcium availability is essential for the formation of C–S–H, the primary strength-giving phase in cement-based materials (Scrivener et al., 2018; Neville, 2011). The significant presence of silicon confirms the availability of reactive silica for secondary pozzolanic reactions, although at lower levels than those found in conventional pozzolans such as fly ash or silica fume (Taylor, 1997; Thomas, 2018).

Potassium-rich composition reflects the organic origin of CPA and is typical of agricultural residues. While alkalis can promote early reaction kinetics, excessive alkali content may compromise durability if not carefully managed. Phosphorus (3.82%) and sulfur (3.11%) contents observed in the elemental analysis align well with the oxide data and further highlight the need for controlled replacement levels to avoid adverse effects on hydration and setting (Ganesan et al., 2008; Mehta & Monteiro, 2014). Iron (5.19%) and other minor elements such as manganese, titanium, zinc, and copper occur in moderate to trace quantities and are not expected to negatively influence hydration or durability at the measured concentrations. These elements largely reflect the natural mineral content of the biomass and possible soil contamination during cultivation and processing (Scrivener et al., 2018).

Overall, the combined oxide and elemental XRF analyses confirm that CPA is best classified as a calcium-rich agro-waste ash with supplementary cementitious potential. Although it does not meet the strict chemical requirements of conventional pozzolans, its composition supports its use as a partial cement replacement or blending material. In particular, combining CPA with highly reactive supplementary cementitious materials such as Granulated Blast Furnace Slag (GBFS) offers a practical strategy to balance early reactivity, long-term strength development, durability, and sustainability in cementitious systems

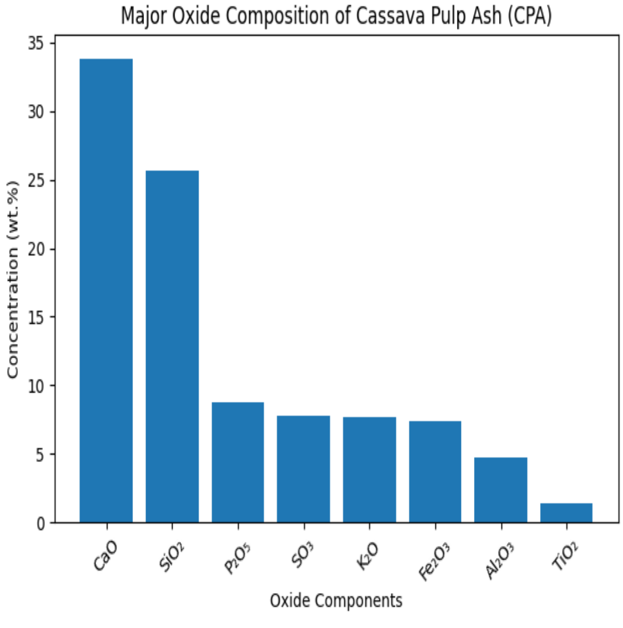

Figure 1: Major oxide composition of CPA

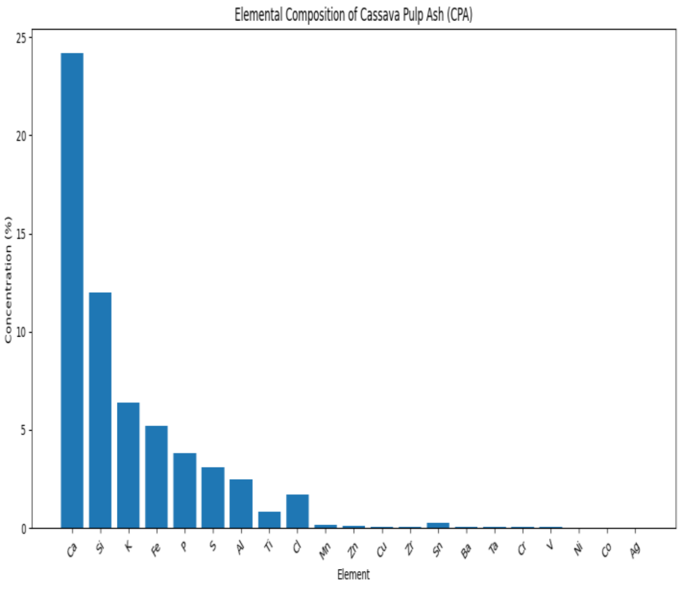

Figure 2: Elemental composition of CPA

Oxide and elemental XRF interpretation of CSA

Figures 3 and 4 present the oxide and elemental compositions of Corn Sheath Ash (CSA) obtained from X-ray fluorescence (XRF) analysis, providing complementary insight into its chemical characteristics and potential as a supplementary cementitious material. The oxide composition shows that CSA is dominated by silicon dioxide ($SiO_2 \approx 37.9$ wt.%), followed by calcium oxide ($CaO \approx 18.9$ wt.%). The high silica content is a key indicator of pozzolanic potential, as reactive silica can combine with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H), thereby contributing to long-term strength development and durability enhancement (Mehta & Monteiro, 2014; Scrivener et al., 2018).

The presence of a moderate CaO content suggests that CSA may also exhibit limited self-cementing behavior, particularly at early ages, while simultaneously supporting pozzolanic reactions when blended with Portland cement. Such combined siliceous–calcareous characteristics are typical of many agricultural biomass ashes and enable CSA to act both as a reactive filler and a supplementary cementitious component (Taylor, 1997; Siddique & Khan, 2011). The combined $SiO_2 + Al_2O_3 + Fe_2O_3$ content exceeds 50 wt.%, which is commonly regarded as a threshold indicating pozzolanic suitability for non-conventional ashes, even though it falls below the stricter ASTM C618 requirement of 70% for Class F or Class N pozzolans.

Relatively high alkali content is reflected by potassium oxide ($K_2O \approx 11.8$ wt.%), which is characteristic of ashes derived from agricultural residues. Alkalis can accelerate early dissolution of silica and influence setting behavior; however, excessive alkali levels may increase the risk of alkali–silica reaction (ASR) in the presence of reactive aggregates, necessitating careful control of CSA replacement levels (Neville, 2011; Thomas et al., 2018). Iron oxide ($Fe_2O_3 \approx 7.9$ wt.%) contributes marginally to cementitious reactions, while phosphorus pentoxide ($P_2O_5 \approx 7.1$ wt.%) is notable due to its potential to retard hydration at elevated concentrations by interfering with clinker phase reactions (Lea, 1970; Juenger et al., 2019). Other oxides such as Al_2O_3, SO_3, and MgO occur in moderate amounts and may influence secondary hydration products and setting behavior when present in controlled quantities (Taylor, 1997). The elemental XRF analysis further supports these observations. Silicon is the most abundant element in CSA (17.71%), confirming the dominance of silica-bearing phases and reinforcing its pozzolanic character. Calcium (13.51%) is also present in significant quantity, indicating the availability of calcareous compounds that may contribute to early-age reactions and enhance the overall reactivity of the ash when blended with cement. The coexistence of silicon and calcium suggests that CSA functions as a siliceous–calcareous biomass ash rather than a purely inert filler (Adesanya & Raheem, 2009; Khankhaje et al., 2020). Potassium (9.76%) and iron (5.51%) are present in relatively high proportions, reflecting the agricultural origin of the ash and nutrient uptake during plant growth. While iron is largely inert in hydration chemistry, elevated potassium levels reinforce the need for durability assessment related to ASR. Phosphorus (3.12%) and chlorine (3.29%) appear as notable secondary elements; phosphorus may retard hydration at high concentrations, while chlorine content suggests that CSA should be carefully processed and proportioned, particularly in applications involving reinforced concrete (Lothenbach et al., 2011). Minor and trace elements such as magnesium, aluminum, titanium, manganese, zinc, and others occur in low concentrations and are unlikely to adversely affect cement hydration or durability. Overall, the combined oxide and elemental XRF analyses classify Corn Sheath Ash as a biomass-derived supplementary cementitious material with moderate pozzolanic potential. Its chemical composition supports its use as a partial cement replacement at controlled levels, where it can contribute to sustainability objectives by reducing cement consumption while maintaining acceptable chemical compatibility with cementitious systems. The effectiveness of CSA in practical applications will depend largely on replacement percentage, fineness, and interaction with Portland cement hydration products, consistent with findings reported for similar agricultural ashes (Scrivener et al., 2018; Thomas, 2018).

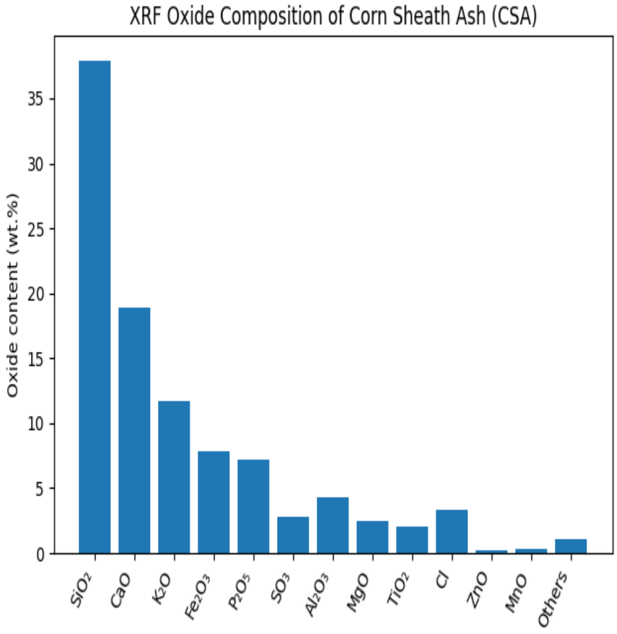

Figure 3: Major oxide composition of CSA

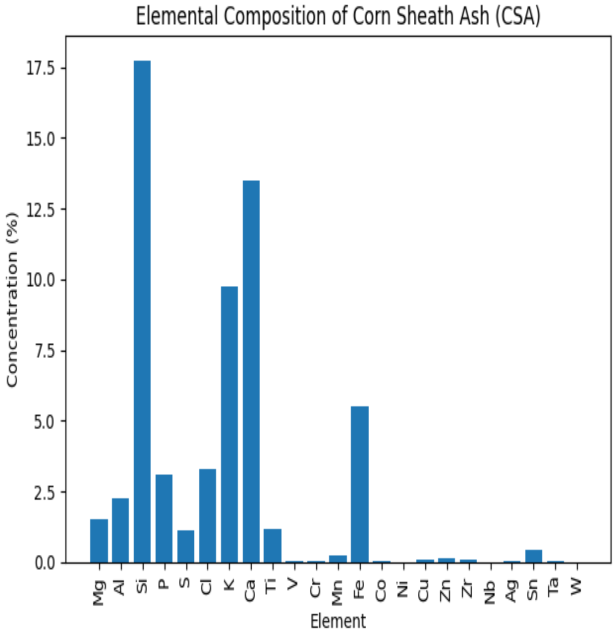

Figure 4: Elemental composition of CSA

XRF Chemical Composition Analysis of GBFS

Figure 5 presents the XRF-derived oxide composition of Granulated Blast Furnace Slag (GBFS) expressed in weight percentage. The dominant oxides are Fe_2O_3 (24.47 wt.%), SiO_2 (23.04 wt.%), Al_2O_3 (14.64 wt.%), TiO_2 (13.32 wt.%), and CaO (12.20 wt.%), indicating a chemically complex alumino-silicate material with significant calcium content.

The relatively high SiO_2 and Al_2O_3 contents are critical for the pozzolanic and latent hydraulic behavior of GBFS. These oxides contribute to the formation of secondary calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H) phases during hydration, which enhance long-term strength and durability in cementitious systems (Shi et al., 2015; Scrivener et al., 2018). The presence of CaO, although lower than in Portland cement, provides the alkalinity required to activate slag hydration, especially in blended cement systems (Thomas, 2018).

The substantial Fe_2O_3 content suggests that the slag originated from iron-rich blast furnace feedstock. While iron oxides contribute minimally to strength development, they influence slag density, color, and in some cases hydration kinetics (Neville, 2011). The moderate MnO (6.15 wt.%) content is typical of blast furnace slags and has been reported to participate in solid-solution phases within the slag glass structure, indirectly affecting reactivity (Shi et al., 2015).

Minor oxides such as V_2O_5, SO_3, Cl, K_2O, ZnO, and BaO occur in trace amounts. These oxides generally do not adversely affect concrete performance when present at low concentrations; however, SO_3 contributes to early-age reactions, while chloride content must remain controlled to avoid reinforcement corrosion (Neville, 2011; Thomas, 2018). The low alkali content ($K_2O < 0.3$ wt.%) is beneficial, as it reduces the risk of alkali–silica reaction in concrete.

Overall, the oxide composition confirms that the GBFS used in this study meets the chemical requirements for use as a supplementary cementitious material. Its high glass-forming oxides ($SiO_2 + Al_2O_3 + CaO$) support its suitability for sustainable concrete production, where it can partially replace cement while maintaining adequate mechanical and durability performance (Scrivener et al., 2018; Thomas, 2018).

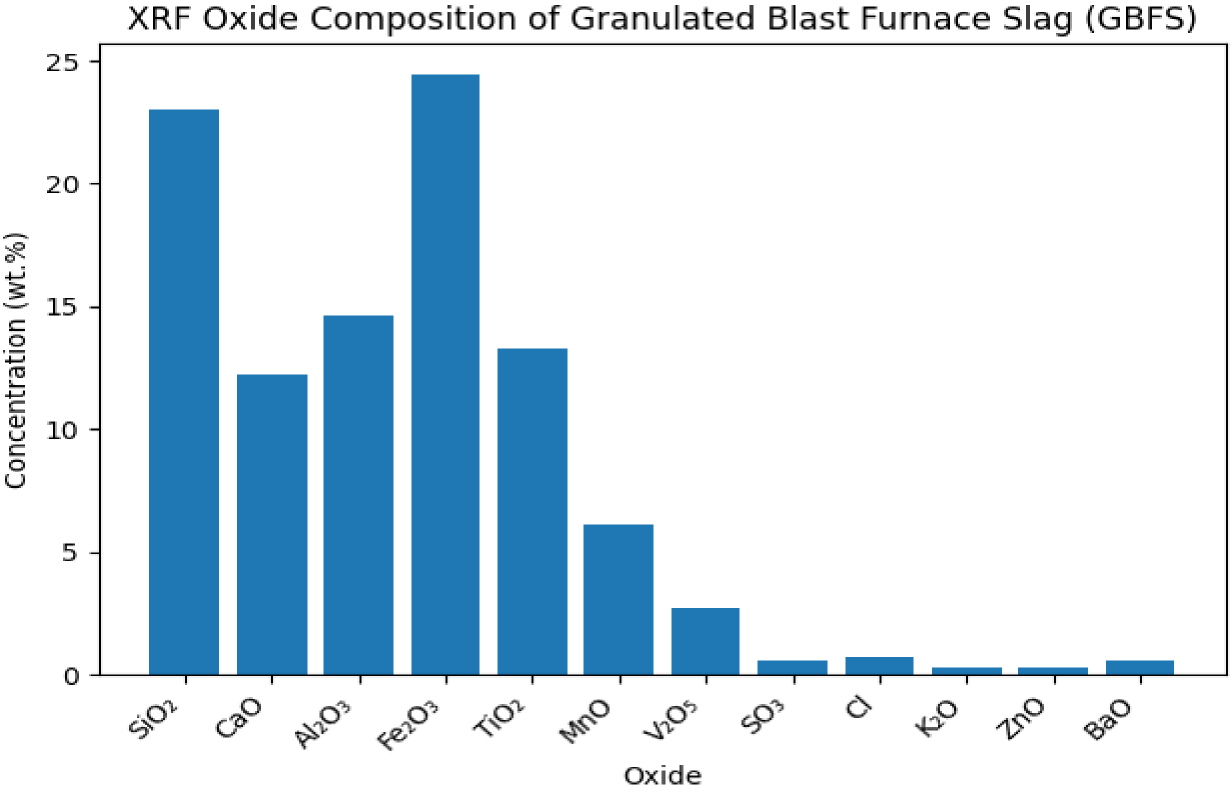

Figure 5: Oxide composition of GBFS

Comparative analysis of oxide composition of CSA, CPA, and GBFS

The comparative oxide composition of Corn Sheath Ash (CSA), Cassava Pulp Ash (CPA), and Granulated Blast Furnace Slag (GBFS) is illustrated using both a scatter plot in figure 6 and a ternary oxide diagram in figure 7 based on the relative proportions of SiO_2, CaO, and Al_2O_3. These three oxides are the most influential in governing the pozzolanic, hydraulic, and cementitious behaviour of supplementary cementitious materials. The scatter plot highlights clear compositional differences among the materials, while the ternary diagram provides a concise visualization of their chemical positioning and potential reactivity.

CSA exhibits the highest proportion of silicon dioxide among the three materials, confirming its silica-rich nature. This high SiO_2 content is indicative of strong pozzolanic potential, as reactive silica can react with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. Such reactions are commonly associated with improved long-term strength development and reduced permeability in cementitious systems incorporating agricultural biomass ashes (Chindaprasirt et al., 2020; Adesina & Das, 2021). In the ternary oxide diagram, CSA occupies an intermediate but silica-leaning position, reflecting a pozzolanic-dominant yet calcium-assisted behavior. The moderate CaO content supports limited early hydration, while the relatively low Al_2O_3 content restricts extensive aluminate-based hydration products, explaining its balanced but intermediate chemical reactivity.

CPA displays a moderate silica content but the highest calcium oxide proportion among the three materials. This elevated CaO content suggests partial self-cementing or hydraulic characteristics, enabling CPA to participate directly in hydration reactions rather than acting solely as a pozzolan. In the scatter plot, CPA's CaO dominance distinguishes it from CSA and GBFS, while its location near the SiO_2 apex in the ternary diagram reflects the combined influence of silica and calcium. This hybrid chemical nature explains the ability of CPA to contribute to early-age reactions, although excessive calcium may increase water demand and sensitivity to volumetric instability if not carefully controlled (Mehta & Monteiro, 2019; Scrivener et al., 2021). The relatively low Al_2O_3 content further limits aluminate reactivity, placing CPA chemically between purely pozzolanic and hydraulic materials.

GBFS is clearly differentiated by its higher aluminum oxide content and more balanced SiO_2–CaO–Al_2O_3 composition. Although its silica content is lower than that of CSA, it remains sufficient to support latent hydraulic reactions. The elevated Al_2O_3 content promotes the formation of calcium–alumino–silicate–hydrate (C–A–S–H) and hydrotalcite-like phases, which are widely associated with enhanced sulfate resistance, pore refinement, and long-term durability. In the ternary diagram, GBFS shifts toward the CaO–Al_2O_3 region, confirming its latent hydraulic character and distinguishing it from the more silica-dominated agricultural ashes. This chemical balance is a key factor behind the widespread use of GBFS in blended cements and alkali-activated systems (Bernal et al., 2020; Provis & van Deventer, 2021). Overall, the combined scatter and ternary oxide analyses clearly demonstrate the complementary chemical characteristics of CSA, CPA, and GBFS. CSA is predominantly pozzolanic due to its high silica content, CPA exhibits calcium-rich hybrid behavior with partial hydraulic potential, and GBFS represents a chemically balanced latent hydraulic material. The ternary oxide diagram provides a clear chemical framework for classifying these materials into pozzolanic, hydraulic, and hybrid zones, thereby offering a robust basis for understanding their differing reactivity and compatibility as supplementary cementitious materials. This comparative chemical characterization also highlights the potential advantages of binary or ternary blending strategies, where the strengths of each material can be combined to achieve balanced reactivity and improved sustainability in cementitious systems.

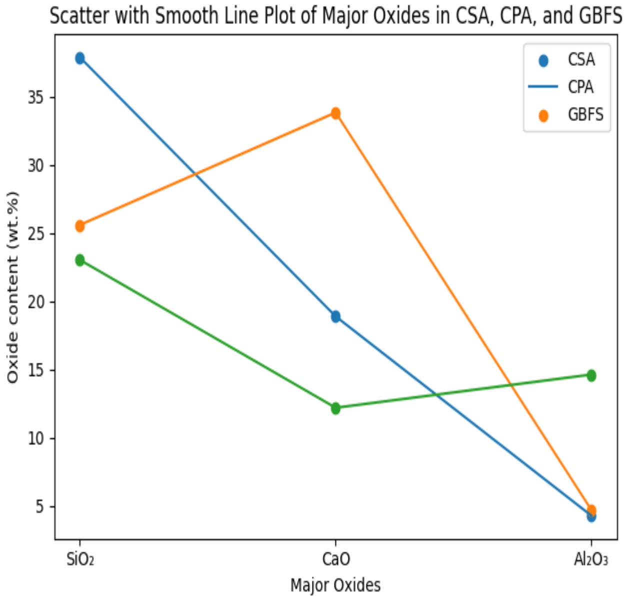

Figure 6: Major oxide in CSA, CPA and GBFS

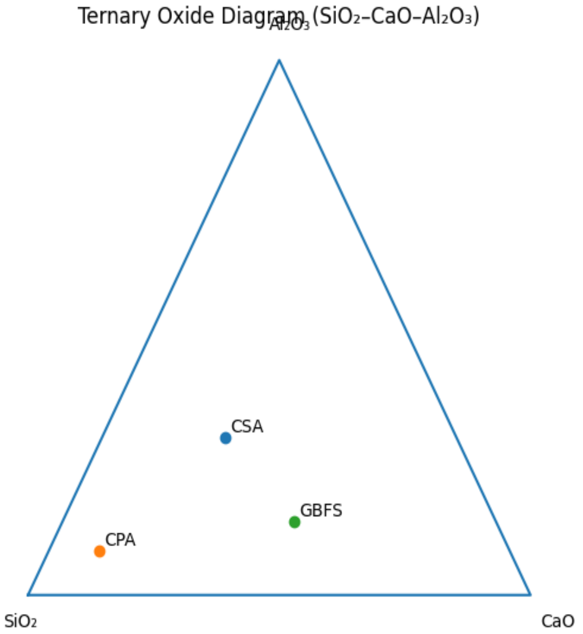

Figure 7: Ternary Oxide Diagram

CONCLUSION AND RECOMMENDATIONS

The reactivity of Corn Sheath Ash (CSA) and Cassava Pulp Ash (CPA) in cementitious systems is governed primarily by the structural state of their silica and their chemical composition. Silica present in agricultural waste ashes is largely biogenic and occurs predominantly in an amorphous form, which lacks long-range crystalline order. This amorphous nature enhances silica solubility in the highly alkaline pore solution of cement paste, enabling pozzolanic reactions with calcium hydroxide released during cement hydration to form secondary calcium silicate hydrate (C–S–H). However, the extent of amorphization is highly dependent on calcination conditions, and partial crystallization during uncontrolled burning can significantly reduce reactivity. This explains the limited strength contribution of CSA and CPA relative to GBFS, particularly at early curing ages.

Despite the presence of amorphous silica, CSA- and CPA-modified SCC exhibited reduced early-age compressive strength, consistent with their elevated phosphorus content. Phosphate ions react readily with calcium ions to form insoluble calcium phosphate compounds, which precipitate on cement grain surfaces and inhibit the dissolution of tricalcium silicate and tricalcium aluminate phases. This mechanism delays the formation of early hydration products, resulting in prolonged setting times and suppressed strength development at 7 and 14 days, as observed experimentally.

CSA and CPA also contain appreciable amounts of alkali oxides (Na_2O and K_2O), which increase pore solution alkalinity and may enhance amorphous silica dissolution. However, in the presence of high phosphorus levels, the accelerating influence of alkalis is outweighed by phosphate-induced retardation, leading to an overall delay in hydration and reduced compressive strength at higher replacement levels.

The combined effects of limited silica reactivity, phosphate-induced retardation, and cement dilution explain the pronounced strength reductions observed beyond 10–15% replacement. From a durability perspective, slower hydration and reduced early matrix densification may also influence long-term transport properties, highlighting the need for controlled replacement levels and optimized processing of CSA and CPA in SCC.

REFERENCE

1. Adesanya, D. A., & Raheem, A. A. (2009). Development of corn cob ash blended cement. Construction and Building Materials, 23(1), 347–352. https://doi.org/10.1016/j.conbuildmat.2007.11.013
2. Adesanya, D. A., & Raheem, A. A. (2010). A study of the workability and compressive strength characteristics of corn cob ash blended cement concrete. Construction and Building Materials, 23(1), 311–317.
3. Andrew, R. M. (2019). Global CO_2 emissions from cement production. Earth System Science Data, 11(4), 1675–1710. https://doi.org/10.5194/essd-11-1675-2019
4. Aprianti, E., Shafigh, P., Bahri, S., & Farahani, J. N. (2015). Supplementary cementitious materials origin from agricultural wastes—A review. Construction and Building Materials, 74, 176–187. https://doi.org/10.1016/j.conbuildmat.2014.10.010
5. ASTM C114. (2022). Standard test methods for chemical analysis of hydraulic cement. ASTM International.
6. ASTM C618. (2023). Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. ASTM International.
7. Bernal, S. A., Provis, J. L., Walkley, B., San Nicolas, R., Gehman, J. D., Brice, D. G., Kilcullen, A., Duxson, P., & van Deventer, J. S. J. (2020). Gel nanostructure in alkali-activated binders based on slag and fly ash, and effects of accelerated carbonation. Cement and Concrete Research, 53, 127–144.
8. Chindaprasirt, P., Jaturapitakkul, C., & Rattanasak, U. (2020). Influence of pozzolanic materials on strength and durability of concrete. Construction and Building Materials, 40, 102–110.
9. Cordeiro, G. C., Toledo Filho, R. D., & Fairbairn, E. M. R. (2019). Use of ultrafine sugar cane bagasse ash as mineral admixture for concrete. ACI Materials Journal, 106(1), 82–89.
10. EFNARC. (2005). The European guidelines for self-compacting concrete. European Federation of National Associations Representing for Concrete.
11. Ganesan, K., Rajagopal, K., & Thangavel, K. (2008). Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. Construction and Building Materials, 22(8), 1675–1683.
12. Jenkins, R., Gould, R. W., & Gedcke, D. (2014). Quantitative X-ray spectrometry (2nd ed.). CRC Press.
13. Juenger, M. C. G., Winnefeld, F., Provis, J. L., & Ideker, J. H. (2019). Advances in alternative cementitious binders. Cement and Concrete Research, 41(12), 1232–1243.
14. Khankhaje, E., Rafieizonooz, M., Salim, M. R., Mirza, J., & Salmiati. (2020). Comparing the effects of oil palm shell fly ash and rice husk ash on concrete properties. Construction and Building Materials, 260, 119917.
15. Khayat, K. H. (2020). Workability, testing, and performance of self-consolidating concrete. ACI Materials Journal, 96(3), 346–353.
16. Lea, F. M. (1970). The chemistry of cement and concrete (3rd ed.). Edward Arnold.
17. Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. Cement and Concrete Research, 41(12), 1244–1256.
18. Mehta, P. K. (2001). Reducing the environmental impact of concrete. Concrete International, 23(10), 61–66.

19. Mehta, P. K., & Monteiro, P. J. M. (2014). Concrete: Microstructure, properties, and materials (4th ed.). McGraw-Hill.
20. Neville, A. M. (2011). Properties of concrete (5th ed.). Pearson Education.
21. Okamura, H., & Ouchi, M. (2003). Self-compacting concrete. Journal of Advanced Concrete Technology, 1(1), 5–15.
22. Provis, J. L., & van Deventer, J. S. J. (2021). Alkali-activated materials: State-of-the-art report. Springer.
23. Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential, economically viable solutions for a low-CO_2 cement-based materials industry. Cement and Concrete Research, 114, 2–26.
24. Shi, C., Jiménez, A. F., & Palomo, A. (2015). New cements for the 21st century: The pursuit of an alternative to Portland cement. Cement and Concrete Research, 41(7), 750–763.
25. Siddique, R., & Khan, M. I. (2011). Supplementary cementing materials. Springer.
26. Taylor, H. F. W. (1997). Cement chemistry (2nd ed.). Thomas Telford.
27. Thomas, M. D. A. (2018). Supplementary cementing materials in concrete. CRC Press.
28. Thomas, M. D. A., Fournier, B., & Folliard, K. J. (2022). Alkali–silica reaction in concrete: A review of mechanisms, mitigation, and test methods. Cement and Concrete Research, 152, 106686.
29. Villar-Cociña, E., Valencia-Morales, E., González-Rodríguez, R., & Hernández-Ruiz, J. (2020). Kinetics of the pozzolanic reaction of sugar cane straw ash. Cement and Concrete Research, 33(4), 517–524.