

## Microstructural Investigation of the Thermal Effect of Bamboo Leaf Ash in Self-Compacting Concrete: A Review

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### Abstract

Self-compacting concrete (SCC) provides high flowability and consolidation without mechanical vibration, but its relatively high cement and powder contents increase both environmental impact and vulnerability to thermally induced deterioration. This review examines the microstructural and thermal effects of bamboo leaf ash (BLA) as a partial cement replacement in SCC, with emphasis on pozzolanic reaction, pore refinement, interfacial transition zone (ITZ) modification, hydration products, and residual performance after elevated-temperature exposure. The reviewed literature indicates that BLA generally contains a high proportion of silica and can contribute to secondary calcium-silicate-hydrate (C-S-H) formation when adequately processed. Reported investigations commonly examine BLA replacement levels of approximately 5–15%, while recent studies indicate effective performance around 8–12% and identify 10% replacement as a promising level under several concrete conditions. Recent experimental evidence has also demonstrated improved mechanical or microstructural performance at approximately 10% BLA, although the response depends strongly on ash production temperature, particle size, water-to-binder ratio, curing, and concrete composition. At elevated temperatures, BLA-modified cementitious matrices may benefit from reduced calcium hydroxide content and refined pore structure; however, the dense matrix of SCC can also increase vulnerability to vapor-pressure development and thermal cracking. The review concludes that BLA has potential as a sustainable supplementary cementitious material for SCC, but the available evidence does not yet justify a universal optimum replacement level or a definitive fire-resistance claim. It is therefore recommended that future research combine SEM/EDS, XRD, TGA/DTG, pore-structure characterization, and residual mechanical testing using controlled heating and cooling regimes. Standardized experimental protocols and quantitative comparisons of BLA-SCC at elevated temperatures are particularly required to establish reliable design recommendations.

**Keywords:** Self-Compacting Concrete, Bamboo Leaf Ash, Microstructural Behavior, Thermal Effects, Sustainability.

### 1.0 Introduction

Self-compacting concrete (SCC) is a modern concrete technology designed to flow and consolidate under its own weight, eliminating the need for mechanical vibration. This property makes SCC particularly suitable for structures with dense reinforcement or complex formwork, offering advantages such as uniformity, reduced labor, and improved surface finish [1]. Its development reflects the increasing demand for high-performance concrete that are easier to place and more durable in challenging construction environments. Alongside these technological advances, sustainability has become a key consideration in concrete research. Cement production is responsible for a significant portion of global carbon emissions, which has driven interest in supplementary cementitious materials (SCMs) derived from industrial or agricultural by-products. These materials not only reduce the cement content in concrete but can also improve long-term durability through pozzolanic reactions [2]. Bamboo leaf ash (BLA) is an agricultural waste product that has emerged as a promising SCM. When properly calcined, BLA is rich in amorphous silica and exhibits pozzolanic activity, which can refine the microstructure of concrete and enhance mechanical performance at later ages [3]. Although research has demonstrated the potential of BLA in normal vibrated concrete, its behavior in SCC remains less explored. SCC relies on a delicate balance of fines, admixtures, and rheological properties, and the incorporation of BLA can influence both fresh and hardened characteristics in ways that differ from conventional concrete. Concrete exposed to elevated temperatures undergoes chemical and microstructural changes such as dehydration of calcium-silicate-hydrate, microcracking, and loss of strength [4]. The inclusion of pozzolanic materials like BLA may influence these thermal responses by refining pore structure and modifying hydration products, but studies focusing specifically on BLA-modified SCC under heat are limited.

The motivation for incorporating bamboo leaf ash (BLA) into self-compacting concrete (SCC) stems from the environmental impact of Portland cement, the high powder demand of SCC, and the need to improve its thermal stability. Due to its high silica content and pozzolanic potential, BLA can consume calcium hydroxide and promote additional C-S-H formation, potentially refining the pore structure and modifying the interfacial transition zone (ITZ). However, the dense matrix of SCC may influence moisture movement, vapour pressure, and thermal cracking during heating. Although recent studies continue to demonstrate the potential of BLA as a supplementary cementitious material, its coupled microstructural and thermal behaviour in SCC remains

insufficiently understood. This review therefore examines how BLA-induced changes in hydration, pore structure, and ITZ characteristics affect the thermal response and residual performance of SCC, while identifying key areas requiring further experimental investigation.

This research aims to address these gaps by investigating the microstructural and thermal behavior of SCC containing BLA, using techniques such as TGA, DTA and SEM. Understanding these interactions will contribute to the development of more sustainable and thermally resilient SCC mixtures, while providing insight into the mechanisms through which BLA influences microstructure and residual performance after heating. Although bamboo leaf ash (BLA) has been extensively explored as a supplementary cementitious material in conventional concrete and high-performance cement-based systems, research on its incorporation into self-compacting concrete (SCC), particularly its performance under elevated temperatures, remains relatively limited and fragmented. Existing studies have predominantly examined aspects such as chemical composition, pozzolanic reactivity, compressive strength, durability, and environmental sustainability. However, comparatively little attention has been given to understanding how BLA-induced microstructural alterations influence the thermal degradation and residual performance of SCC following exposure to high temperatures.

The novelty of this review is its integrated microstructural and thermal perspective on BLA-modified SCC. Instead of treating BLA solely as a partial cement replacement, the review establishes a connection between its physicochemical properties and key microstructural characteristics, including hydration-product development, pore-structure refinement, interfacial transition zone (ITZ) modification, thermal microcracking, and residual mechanical performance after heating. In addition, the review examines how different heating and cooling regimes affect the thermal response, degradation mechanisms, and post-heating behaviour of BLA-incorporated SCC.

## 2.0 Self-Compacting Concrete and Supplementary Materials

### 2.1 Properties and Requirements of SCC

Self-compacting concrete (SCC) is formulated to be highly flowable and non-segregating, capable of completely filling formwork and encapsulating reinforcement purely under its own weight without the need for mechanical vibration. To function effectively, fresh SCC relies on an optimized mix of cement, fine and coarse aggregates, water, fillers, superplasticizers, and viscosity-modifying agents (VMAs). The fundamental difference in passing behavior between conventional vibrated concrete and SCC is illustrated in Figure .1 It must achieve a delicate balance of three fundamental properties [5], [1]:

**Filling ability:** The capacity to flow under its own weight and fill complex formwork completely. This is achieved using high-range water-reducing admixtures and an increased powder content, and is typically quantified by a slump flow diameter between 550–850 mm.

**Passing ability:** The ability to navigate through narrow gaps and dense reinforcement without blocking or clogging. Proper aggregate grading and VMAs facilitate this smooth movement [6].

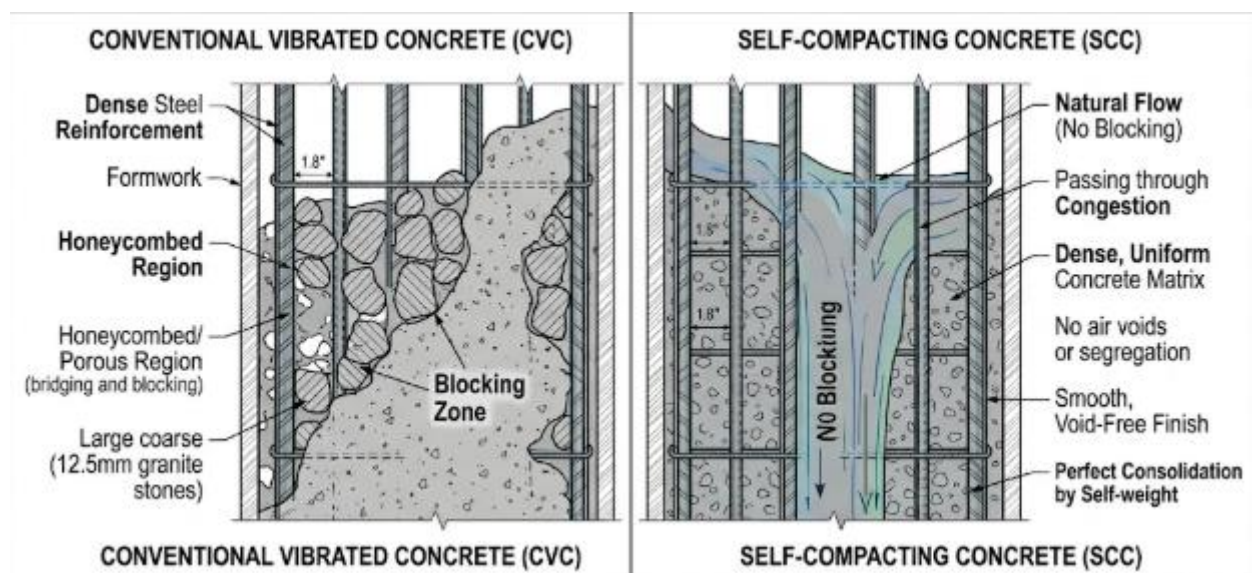


Figure 1: Comparison of passing ability between CVC & SCC

Source: [1]

**Segregation resistance:** The stability of the mix to prevent coarse aggregates from settling or mortar from separating during placement. This is maintained by adjusting the matrix viscosity and ensuring an adequate fines content [7].

While the higher binder and fines requirements in SCC enhance cohesiveness and flowability, they also increase the embodied energy and carbon footprint of the concrete, necessitating the use of sustainable alternatives.

## 2.2 The Role and Benefits of SCMs in SCC

To offset the environmental impacts of the high cement content required in SCC, supplementary cementitious materials (SCMs) are integrated as partial cement replacements. SCMs such as fly ash, silica fume, metakaolin, and agricultural ashes can act as either pozzolanic materials or micro-fillers. Pozzolanic SCMs contain reactive silica or alumina that chemically react with calcium hydroxide (a cement hydration byproduct) to form additional calcium silicate hydrate (C–S–H).

The incorporation of SCMs in SCC offers several critical benefits for both fresh and hardened properties:

**Improved Workability:** Finely ground pozzolanic materials act as micro-fillers that improve the flowability and cohesion of SCC, enhancing filling and passing ability even at lower water-cement ratios.

**Microstructural Refinement:** SCMs fill voids between cement particles and aggregates, while their pozzolanic reactions generate secondary C–S–H. This strengthens the cement matrix, reduces porosity, and enhances bonding in the interfacial transition zone (ITZ) [8].

**Enhanced Durability:** The resulting denser microstructure significantly improves the concrete's resistance to chemical threats, such as chloride ingress, sulfate attack, and carbonation, extending the structure's service life [8].

**Environmental Sustainability:** By partially substituting traditional cement, SCMs lower the overall embodied energy and carbon dioxide emissions associated with concrete production, supporting sustainable construction practices [8].

## 3.0 Bamboo Leaf Ash (BLA) as a Cementitious Material

Bamboo leaf ash (BLA) is an agricultural by-product obtained from the controlled burning of bamboo leaves, offering a sustainable opportunity to convert waste into a value-added construction material while mitigating the environmental pollution associated with open-air burning. Utilizing these leaves provides a renewable supplementary cementitious material that aligns with environmental management practices and supports circular economy principles in construction. The production of highly reactive BLA requires controlled combustion temperatures, typically between 600 °C and 700 °C, to maximize silica content while preventing the silica from crystallizing and losing its amorphous, reactive phases [9]. Once burned, the ash is typically ground or sieved to achieve a fine particle size, allowing it to act efficiently as a micro-filler when incorporated into concrete.

The performance of BLA in self-compacting concrete is largely dictated by its distinct chemical and physical properties. BLA is characterized by a high silica ( $\text{SiO}_2$ ) content, generally ranging from 60% to 85%, alongside smaller quantities of alumina ( $\text{Al}_2\text{O}_3$ ), iron oxide ( $\text{Fe}_2\text{O}_3$ ), and calcium oxide ( $\text{CaO}$ ), which collectively determine its pozzolanic reactivity [10], [11]. Crucially, the silica present is largely amorphous, which facilitates its chemical interaction with cement during hydration. Microscopic evaluations have shown that BLA particles are typically irregular and angular, morphological traits that help improve particle packing and matrix cohesion [12]. However, the high surface area and porous nature of the ash inevitably increase the water demand of the mix. In self-compacting concrete applications, this reduction in flowability must be carefully managed through the strategic use of superplasticizers to maintain an optimal balance between workability and structural performance.

The core effectiveness of BLA as a supplementary cementitious material is driven by its pozzolanic reactions, which actively participate in secondary hydration processes within the concrete matrix. During the primary hydration of Portland cement, calcium hydroxide is naturally released as a vulnerable by-product. The amorphous silica in BLA actively reacts with this free lime, consuming it to form secondary calcium silicate hydrate (C–S–H). By generating additional C–S–H, this pozzolanic reaction physically refines the pore structure and significantly increases the density of the hardened paste. Consequently, BLA-modified matrices typically exhibit a more cohesive and compact microstructure with fewer voids and enhanced bonding between fine particles and hydration products. Because BLA provides no initial calcium, it may slightly slow early hydration; however, its high surface reactivity gradually accelerates later-age hydration as more calcium hydroxide becomes available to react. Reducing the volume of free calcium hydroxide directly improves the overall chemical stability of the paste, which is particularly critical under elevated thermal exposure, as a lower calcium hydroxide content results in fewer structural weaknesses related to heat decomposition.

## 4.0 Microstructural and Thermal Behavior of BLA-Modified Concrete

### 4.1 Microstructural Analysis Techniques

The microstructural and thermal behavior of self-compacting concrete (SCC) containing bamboo leaf ash (BLA) can be evaluated using three complementary analytical techniques, each providing distinct insights into the matrix:

**Scanning Electron Microscopy (SEM):** SEM provides high-resolution imaging of the hardened cement paste and the interfacial transition zone (ITZ). In BLA-modified SCC, SEM is utilized to visualize particle distribution, pore refinement, the development of microcracks, and the formation of secondary calcium-silicate-hydrate (C–S–H). Images of BLA-containing mixes typically display a denser, more continuous microstructure compared to control mixes, which serves as a visual indicator of effective pozzolanic activity [13].

**Thermogravimetric Analysis (TGA):** TGA measures the mass change of a concrete sample as it is heated under controlled conditions. In these systems, mass losses directly correspond to water evaporation, C–S–H dehydration, calcium hydroxide (CH) decomposition, and the decarbonation of carbonates. The principal mass-loss and thermal events associated with hydrated cement paste during heating are illustrated schematically in Figure 2. For BLA–SCC, TGA primarily tracks the consumption of CH driven by the pozzolanic reaction; a reduced CH decomposition peak relative to a control mix signifies an active reaction. Additionally, smaller mass losses at elevated temperatures indicate a more thermally stable microstructure [14].

**Differential Thermal Analysis (DTA):** DTA measures the endothermic and exothermic energy events that occur during heating. When paired with TGA, it helps distinguish overlapping reactions, such as CH decomposition and C–S–H dehydration. In BLA–SCC, shifts in decomposition temperatures or peak areas highlight the ash's influence on hydration products, confirming the formation of secondary C–S–H and overall thermal stability [15].

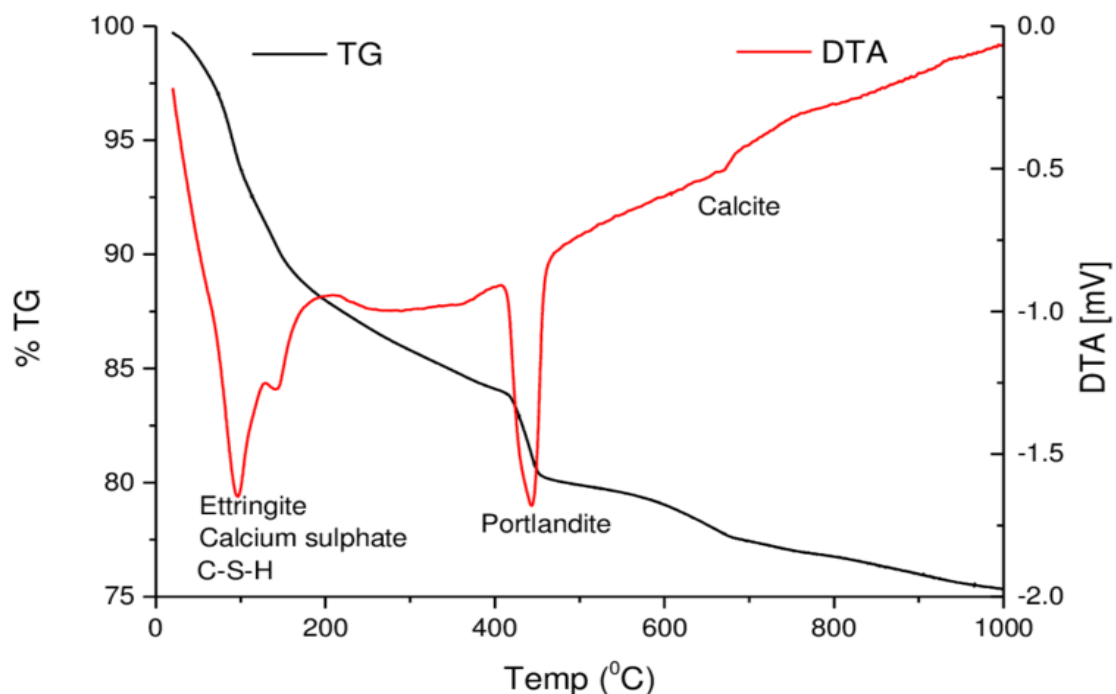


Figure.2: Typical TGA & DTA curves for a hydrated cement paste.

Source: [16]

#### 4.2 Microstructural Changes in BLA-Concrete

The introduction of BLA into a cementitious matrix triggers several physical and chemical microstructural transformations:

**Reduction in Pore Volume:** BLA reduces total porosity and refines the concrete's pore structure. The amorphous silica in the ash reacts with calcium hydroxide to form additional C–S–H, which physically fills capillary pores and narrows the overall pore network, resulting in lower water absorption [17], [18].

**Improved Matrix Densification:** The fine BLA particles act as initial micro-fillers, enhancing particle packing, while the subsequent pozzolanic reaction generates additional C–S–H over time. This dual action produces a highly compact microstructure that improves strength and reduces the ingress paths for water and aggressive agents.

**Influence on the Interfacial Transition Zone (ITZ):** The ITZ, the region surrounding aggregates, is typically the weakest and most porous link in concrete. The fine particles and pozzolanic activity of BLA help densify this zone by producing additional C–S–H, reducing microcracks, and improving the cohesion and bonding between the aggregate and the cement paste [19].

**Morphology of Hydration Products:** The secondary C–S–H gel formed through BLA's pozzolanic reaction is generally finer and more homogeneous than the gel produced by ordinary Portland cement. This uniform morphology, which exhibits fewer needle-like ettringite crystals and less portlandite crystallization, enhances microstructural stability and reduces the likelihood of microcrack initiation under stress or thermal cycling [19].

#### 4.3 Concrete Behavior at Elevated Temperatures

As SCC is exposed to increasing temperatures, it undergoes a series of chemical, physical, and microstructural transformations that directly impact its structural integrity. Exposure to high heat causes a progressive reduction in both compressive and tensile strength, primarily due to the decomposition of hydration products and the internal stresses induced by differential thermal expansion between the cement paste and the aggregates. Research indicates that temperatures exceeding 300 °C cause a significant decline in mechanical properties.

At elevated temperatures, the primary binder, C–S–H, begins to partially dehydrate, causing shrinkage and the development of microcracks within the matrix and the ITZ. This microcracking reduces the load-carrying capacity and increases permeability, accelerating degradation [20], [21]. Above 500 °C, calcium hydroxide begins to partially decompose, followed by the breakdown of carbonates at even higher temperatures [14]. Incorporating pozzolanic materials like BLA helps moderate this strength loss by densifying the microstructure and producing additional C–S–H that actively resists thermal degradation.

#### 4.4 Thermal Performance of SCC Compared to Conventional Concrete

Because of its unique composition, SCC responds differently to elevated temperatures than conventional vibrated concrete (CVC). SCC contains a higher volume of paste and fine materials, which creates a denser and more homogeneous matrix. While this improves early strength and workability, the high fines content causes the thermal conductivity of SCC to decrease as temperatures rise reaching values as low as 1.2 W/mK at 600 °C [22].

Crucially, this dense microstructure and higher retained moisture content make SCC more susceptible to explosive spalling under rapid heating conditions compared to conventional concrete [23]. Both SCC and CVC experience massive strength reductions at high heat, with flexural strength dropping by up to 90% between 450 °C and 600 °C [24]. However, SCC may temporarily exhibit an increase in compressive strength at moderate temperatures (150–300 °C) due to heat-accelerated secondary hydration, before suffering significant losses at higher temperatures.

#### 4.5 Thermal Behavior of Pozzolanic and BLA-Modified Concretes

The inclusion of pozzolanic materials significantly enhances the thermal resilience of self-compacting concrete. By reducing the volume of free calcium hydroxide and synthesizing a denser C–S–H network, mineral additives improve the residual capacity of the concrete, particularly at moderate heat levels [25].

**Residual Strength:** SCC mixes modified with pozzolans retain a much higher proportion of their compressive strength after cooling from temperatures up to 600 °C compared to plain SCC. However, rapid heating can still trap moisture in this densified matrix, leading to internal pressure buildup and spalling [26].

**Microstructural Stability:** Following high-temperature exposure, SEM imaging of pozzolanic SCC reveals zones of relatively intact C–S–H gel and fewer large cracks in binder-rich regions. While the refined pore structure delays severe cracking, microcracks will still eventually form near the ITZ under extreme heat.

**Heating and Cooling Regimes:** The concrete's residual stability is heavily dependent on how it is heated and cooled. Rapid water-quenching causes severe thermal shock and larger strength losses, whereas slower heating rates and air-cooling minimize internal spalling risks by allowing vapor to gradually escape [27].

**BLA-Specific Thermal Resilience:** Although dedicated high-temperature studies on BLA-SCC are still emerging, analogous research shows that geopolymer concrete containing bamboo ash maintains significantly higher residual strength and pulse velocity after being heated to 800 °C [28]. This indicates that BLA effectively enhances thermal stability in SCC through matrix densification and continuous pozzolanic reactions under controlled thermal conditions.

Table 1: Summary of reported BLA replacement levels and observed performance

| S/N | Author | BLA Replacement | Microstructural property investigated | Observation                                                                                                                                                                                            |
|-----|--------|-----------------|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1.  | [29]   | 10–20%          | XRD, SEM/EDX, FTIR, TG/DTG, hydration | BLA showed high pozzolanic activity and promoted formation of C–S–H; TG/DTG identified hydration-related mass losses, providing a basis for understanding thermal decomposition of BLA cement systems. |

| S/N | Author | BLA Replacement                | Microstructural property investigated      | Observation                                                                                                                                                                                          |
|-----|--------|--------------------------------|--------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2.  | [30]   | 5–25%                          | Porosity and cement-paste/mortar structure | Increasing BLA increased apparent porosity and water absorption while reducing bulk density, indicating that BLA content can substantially modify the pore system.                                   |
| 3.  | [3]    | BLA systems                    | XRD, SEM, pozzolanic reaction              | BLA's amorphous silica participates in pozzolanic reactions with $\text{Ca(OH)}_2$ , producing additional cementitious hydrates and modifying the matrix structure.                                  |
| 4.  | [29]   | 5–30%                          | MIP, FESEM, XRD, FTIR, TGA                 | BLA contained predominantly amorphous silica; higher BLA contents produced greater tortuosity/fewer connected pores, demonstrating potential pore refinement.                                        |
| 5.  | [31]   | 5–20%                          | Concrete microstructure and durability     | BLA was classified as a Class N pozzolan; 5–10% replacement improved concrete performance, while increasing BLA altered water demand and hydration characteristics.                                  |
| 6.  | [32]   | 10–30%                         | XRD, TGA, pozzolanic activity              | BLA replacement maintained mortar strength up to 30% under the investigated conditions, supporting the role of pozzolanic reaction and secondary hydration products in matrix development.           |
| 7.  | [33]   | 5–20%                          | SEM and mechanical behaviour               | SEM observations showed improved grain interlocking at 5% BLA, suggesting improved particle–binder interaction and matrix compactness.                                                               |
| 8.  | [34]   | 5–15%                          | SEM/EDX, HPC microstructure                | BLA exhibited irregular/angular particles and pozzolanic characteristics; incorporation, particularly around 10%, improved mechanical and durability properties under normal curing.                 |
| 9.  | [35]   | Various                        | Systematic review of microstructure        | The review of 31 studies concluded that calcination temperature, particle size and amorphous silica strongly influence BLA reactivity and subsequent microstructural development.                    |
| 10. | [36]   | BLA + pumice powder            | SEM, pore structure, C–S–H                 | SEM showed a refined and dense pore structure in the BLA-containing mixture, together with greater occurrence of C–S–H gel, demonstrating the microstructural contribution of BLA.                   |
| 11. | [37]   | BLA + metakaolin               | Microstructure and pore development        | Microstructural assessment showed reduced pore numbers at the investigated BLA–metakaolin level, indicating matrix densification through combined SCM action.                                        |
| 12. | [38]   | BLA-containing fiber cement    | SEM and X-ray microtomography              | BLA affected porosity and pore connectivity; the study demonstrates that BLA can modify the internal pore network, an important parameter for moisture movement during heating.                      |
| 13. | [39]   | 5–15%; ash calcined 500–1000°C | XRD, TGA/DTG, pozzolanic activity          | Calcination temperature strongly influenced BLA reactivity; 600°C produced the highest pozzolanic performance, showing that ash processing can determine subsequent hydration and thermal behaviour. |
| 14. | [40]   | BLA + CDW                      | Pozzolanic reaction/mineralogy             | BLA was investigated as part of a low-carbon ternary cement system, demonstrating                                                                                                                    |

| S/N | Author | BLA Replacement             | Microstructural property investigated | Observation                                                                                                                                                                                                                                                                                    |
|-----|--------|-----------------------------|---------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     |        |                             |                                       | the importance of its reactive silica in producing secondary cementitious phases.                                                                                                                                                                                                              |
| 15. | [41]   | BLA-containing fiber cement | XRD/TGA and gel formation             | BLA enhanced gel formation, providing evidence that its silica-rich chemistry contributes to additional binding phases and matrix modification.                                                                                                                                                |
| 16. | [42]   | 5–10%                       | TGA, FTIR, temperatures up to 1000 °C | This is particularly important for your review: TGA indicated that 5% and 10% BLA mixtures exhibited greater thermal stability than the control, while FTIR showed decreasing $\text{Ca}(\text{OH})_2$ and development of C–S–H-related bonding.                                               |
| 17. | [43]   | Treated/untreated BLA       | Hydration and microstructure          | Water and acid pretreatment modified BLA reactivity and accelerated hydration, demonstrating that BLA processing can influence the development of the cementitious microstructure.                                                                                                             |
| 18. | [44]   | 20–40%                      | TGA, porosity, hydration products     | Recent work directly used TGA to examine hydrated products in BLA cement paste/mortar and evaluated porosity and durability, strengthening the evidence that BLA alters the internal cementitious structure.                                                                                   |
| 19. | [45]   | BLA-containing 3D concrete  | Microstructural mechanisms            | BLA was reported to refine the concrete microstructure through enhanced particle friction and interface bonding, while reducing chloride transport. Although not a thermal study, the result is relevant because pore and interface refinement govern moisture/vapor transport during heating. |

Bamboo leaf ash (BLA) has emerged as a promising supplementary cementitious material because of its silica-rich composition, pozzolanic reactivity, and potential to reduce Portland cement consumption. Studies (Table 1) have shown that BLA can consume calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), promote additional C–S–H formation, refine pore structure, and improve matrix compactness and particle interlocking. However, the microstructural behaviour of BLA-containing self-compacting concrete (SCC) under elevated temperatures remains insufficiently investigated. Heating can cause moisture loss, dehydration of C–S–H and  $\text{Ca}(\text{OH})_2$ , pore coarsening, thermal incompatibility, and microcracking, which may significantly affect residual strength and durability. Recent thermal analysis of BLA-blended cement paste using TGA and FTIR reported improved thermal stability at 5–10% BLA and evidence of changes in  $\text{Ca}(\text{OH})_2$  and C–S–H phases [42]. Therefore, this review focuses on the relationship between BLA characteristics, hydration products, pore structure, interfacial transition zone, thermal decomposition, microcrack development, and residual performance, while highlighting the limited research integrating BLA, SCC, elevated-temperature exposure, and advanced microstructural techniques such as SEM, XRD, FTIR, TGA/DTG, and porosity analysis.

## 5.0 Conclusion

Based on the literature reviewed, self-compacting concrete (SCC) offers transformative advantages in modern construction, primarily through its ability to consolidate under its own weight without mechanical vibration. However, the high cement and fines content required to achieve these properties increases its environmental footprint, necessitating the integration of sustainable supplementary cementitious materials (SCMs). Bamboo leaf ash (BLA) has emerged as a highly effective agricultural by-product for this purpose.

The literature establishes that when properly calcined, the amorphous silica in BLA actively participates in pozzolanic reactions, consuming vulnerable calcium hydroxide to generate a denser network of secondary calcium-silicate-hydrate (C–S–H) gel. This chemical process fundamentally refines the concrete's pore structure, strengthens the interfacial transition zone, and improves overall matrix cohesion. Furthermore, this microstructural densification translates to enhanced thermal resilience; BLA-modified SCC demonstrates

improved resistance to thermal-induced microcracking and retains greater structural stability at elevated temperatures compared to conventional mixes. Across the reviewed literature, favorable performance has frequently been reported at low-to-moderate BLA replacement levels, commonly within approximately 5 – 15%; however, the optimum level is not universal and depends on BLA processing conditions, chemical composition, particle size, water-to-binder ratio, curing regime and the specific cementitious system. Ultimately, the incorporation of BLA in SCC successfully bridges the gap between high-performance engineering requirements and the critical need for sustainable, low-carbon construction practices.

### 5.1 Recommendations

Drawing from the established research on the microstructural and thermal behavior of BLA-modified SCC, the following recommendations are proposed to guide future applications and studies:

**Implement Advanced Analytical Techniques:** To fully understand the chemical transformations within the concrete matrix, it is highly recommended to continuously utilize complementary methods such as Scanning Electron Microscopy (SEM), Thermogravimetric Analysis (TGA), and Differential Thermal Analysis (DTA). These tools are essential for accurately tracking the consumption of calcium hydroxide and confirming thermal stability.

**Identify and Maintain Optimal Replacement Levels:** Because the high surface area of BLA can negatively impact the workability of fresh SCC, mix designs should strictly calibrate the substitution percentage. Staying within the identified optimal range (5–15%) ensures the concrete gains the microstructural benefits of the pozzolanic reaction without suffering from severe flowability loss or an imbalance of unreacted silica.

**Evaluate Heating and Cooling Variations:** The literature indicates that the residual strength of pozzolanic concrete is heavily influenced by the specific heating and cooling regimes it experiences. Future research should closely examine how different cooling methods (e.g., air-cooling versus rapid water-quenching) affect thermal shock, internal pressure buildup, and the risk of explosive spalling in the dense SCC matrix.

**Target High-Temperature Applications:** Given its improved microstructural integrity and ability to resist the decomposition of hydration products under heat, BLA-modified SCC should be actively considered for structural applications in fire-prone environments or industrial settings that undergo frequent thermal cycling.

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