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# Review of Pozzolanic Materials for Cement Blending and Concrete Applications

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***Abstract***

*The growing environmental concerns associated with cement production, particularly its high carbon footprint, have driven research into sustainable alternatives such as supplementary cementitious materials (SCMs) derived from agricultural and industrial waste. This study synthesizes findings from recent investigations into the pozzolanic potential of basil plant ash (BPA), rice husk ash (RHA), and stockpiled fly ash (FA), evaluating their processing methods, microstructural characteristics, and performance in concrete applications. BPA, being derived by controlled thermal processing, exhibited the best reactivity at 700°C and improved significantly the compressive as well as tensile strength of ultra-high-performance concrete and increased durability. RHA, treated by calibrated grinding and calcining, delivered high amorphous silica content and pozzolanic activity, resulting in significant early-age gain in strength and lowered porosity. FA, typically low-grade because of storage for extended periods, was rejuvenated via mechanical activation (milling), which enhanced surface area and reactivity and rendered it an effective SCM for typical mortar use. The three materials showed decreased permeability, enhanced microstructure, and hydration process compatibility, leading to long-term durability of concrete. Aside from technical advantages, application of these materials meets key environmental objectives by lowering $CO_2$ emissions, reducing industrial and agricultural waste, and saving natural resources. They also represent low-cost solutions to conventional cement components economically, supporting circular economy and sustainable development principles. However, consistent performance depends heavily on optimized processing, standardized treatment protocols, and further validation of long-term behavior. This study concludes that BPA, RHA, and FA hold strong promise as sustainable SCMs and encourages further interdisciplinary research to advance green concrete technologies through scalable, cost-effective, and environmentally responsible practices.*

**Keywords:** Pozzolanic materials, supplementary cementitious materials (SCMs), basil plant ash (BPA), rice husk ash (RHA), fly ash (FA), sustainable concrete, cement replacement, thermal treatment, mechanical activation, circular economy

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## INTRODUCTION

Concrete plays a foundational role in shaping modern infrastructure, forming the backbone of buildings, bridges, roads, and numerous civil engineering applications [1]. However, its environmental footprint is a growing concern, especially considering that cement, one of the key constituents of concrete, is responsible for approximately 8% of the global carbon dioxide emissions [2]. The manufacture of only one tonne of cement releases around 0.9 tonnes of $CO_2$ owing to the high-energy calcination process and fossil-fuel combustion. Widespread environmental concerns have accelerated the worldwide search for sustainable substitutes that can curb reliance on normal Portland cement (OPC) without sacrificing the performance attributes of concrete [3].

Supplementary cementitious materials (SCMs) have become potential alternatives to OPC, with the possibility of partial replacement of OPC by industrial and agricultural wastes. SCMssuch as fly ash (FA), rice husk ash (RHA), and basil plant ash (BPA)possess pozzolanic activity. In combination with water and calcium hydroxide liberated during the hydration of cement, SCMs create an extra calcium silicate hydrate (C-S-H) gel, which contributes to the strength and durability of concrete. Their integration not only enhances mechanical performance but also solves the most important problems of waste management, environmental pollution, and resource protection. Therefore, SCM application is consistent with the objectives of sustainable development and furthers the principles of a circular economy [4].

Recent research has shown that, with correct processing, industrial residues such as FA and agricultural wastes such as BPA and RHA can both serve as SCMs. However, calcination, grinding, and activation techniques, which affect the chemical reactivity, particle size distribution, and cement compatibility of these materials, have a significant impact on their effectiveness. This study examined developments in the characterization, processing, and use of FA, RHA, and BPA as SCMs. It evaluates their potential to enhance concrete sustainability, mechanical performance, and long-term durability in construction applications by combining the results of several studies [5].

## ANALYSIS OF REVIEWED STUDIES

### Investigation into Ultra-High-Performance Concrete with Basil Plant Ash (BPA)

In the first study, BPA was investigated as a potential cement substitute for ultra-high-performance concrete (UHPC). The important conclusions are as follows [6].

- *Processing:* BPA was heat-treated at 300°C to 900°C and integrated into UHPC mixes at replacement levels ranging from 5% to 25% of ordinary Portland cement (OPC). optimum pozzolanic reactivity was achieved when the feedstock was treated at 700 °C. This converts the feed downstream to a highly reactive SCM material during calcination.
- *Characterization:* The use of BPA has shown significant development in terms of pozzolanic activity, which has been verified through X-ray diffraction (XRD) and thermogravimetric analysis (TGA), as well as its high amorphous silica content. Scanning electron microscopy (SEM) showed finer particle sizes and improved surface textures for hydration reactions.
- *Performance:*
  - At the 20% BPA replacement level, the compressive strength increased by 15.07%, and the splitting tensile strength increased by 20.39% when compared with the control mixes. This approach was attributed to better particle packing and the formation of a secondary gel (C-S-H).
  - The durability was enhanced, as evidenced by the reduced sorptivity and water permeability, contributing to longer-lasting concrete structures.
- *Environmental Implications:* BPA offers a sustainable alternative by utilizing agricultural waste, reducing the OPC content, and mitigating environmental impacts.

### Optimizing Rice Husk Ash (RHA) for Cement Blending

Reconsidering different thermomechanical treatments as an SCM for RHA is the primary goal of the second study. Some key considerations include [7]:

- *Processing:* RHA was subjected to grinding and burning at various temperatures (400°C to 800°C) and durations. Burning at 700°C resulted in optimal pozzolanic activity by producing amorphous silica.
- *Characterization:*
  - Loss on ignition (LOI) tests showed decreased unburnt carbon at higher temperatures, making RHA more effective as an SCM.

  - SEM images showed that post-treatment reduced the porosity of the foam and established a more uniform particle structure, thus improving the hydration potential.
  - XRF and XRD analyses confirmed a high silica content in the amorphous state, which is critical for effective pozzolanic reactions.
- *Performance:*
  - The control samples have specific compression strengths, which are extensively exceeded by those using RHA replacements, with strength activity index values greater than 80%.
  - The reasons behind the intensified levels of hydration due to the pozzolanic reactivity in RHA have paved the way for better early age strength results.
- *Environmental Implications:* The application of RHA in cement manufacturing solves the basic issue of agricultural waste disposal, reduces the carbon footprint, and provides inexpensive, cost-effective SCM solutions.

**Pozzolanic Activity of Stockpiled Fly Ash (FA)**

The third study focused on the pozzolanic activity of stockpiled FA, which are mostly activated through grinding [8].

- *Processing:* Fly ash (FA), collected from coal-fired power plants, was milled from 0 min to a maximum of 180 min. Extended milling increases the specific surface area and improves the reactivity of the particles.
- *Characterization:*
  - Milling transformed FA's morphology, enhancing its reactivity and pozzolanic activity.
  - The Frattini, Chapelle, and STRENGTH ACTIVITY INDEX (SAI) test supported that the pozzolanic reactivity improvement occurred as a result of activation.
  - Electrical conductivity measurements indicated faster ionic interactions in the milled samples, supporting enhanced hydration kinetics.
- *Performance:*
  - Mortars blended with FA showed an improvement in compressive strength according to milling time, attaining SAI values of over 75% for finely milled samples.
  - Milling decreased the unreactive components, making FA a feasible supplementary cementitious material (SCM).
- *Environmental Implications:* Recycling stockpiled fly ash for use as an SCM not only prevents its accumulation in landfills but also provides a sustainable solution to the dwindling supplies of fly ash made worse by reduced coal power generation.

## COMPARATIVE DISCUSSION

### Material Characteristics and Treatment

The characteristics and treatment processes of supplementary cementitious materials (SCMs) play pivotal roles in enhancing their pozzolanic activity and effectiveness in concrete applications. Each of the reviewed studies emphasized that proper processing is essential for transforming raw agricultural or industrial waste into high-performance SCMs. Thermal treatment has been determined to be the most effective way to activate BPA and rice husk ash (RHA). Controlled burning at approximately 700°C yields the highest content of amorphous silica—a key element for pozzolanic activity [9]. A temperature such as this provides a means of organic material breakdown and the formation of reactive silica phases without extensive crystallization, which would otherwise reduce the pozzolanic activity. For fly ash (FA), mechanical activation through milling is the most effective approach because of its ability to enhance physical properties, such as fineness and surface area. Greater milling durations, ideally 180 min, are required, which result in finer particles, greater reactivity, increased surface-to-volume ratio, accelerated hydration reactions, and improved incorporation within the cement matrix [10]. In contrast to thermally treated products, FA is more dependent on physical transformations than chemical modifications in an attempt to enhance its performance [11]. These results demonstrate the necessity for personalized treatment techniques that rely on the inherent nature of each material. Although thermal activation optimizes the chemical composition and phase structure of BPA and RHA, mechanical activation is suitable for altering the morphology of FA [12]. In addition, recognizing the interrelationship between treatment parameters and material response is significant for ensuring uniformity of performance and quality in SCM manufacturing. As these processes continue to improve and be optimized, they provide a definite road map to convert waste materials into valuable, sustainable inputs for green concrete manufacturing [13].

**Impact on Concrete Properties**

Pozzolanic additives, such as fly ash (FA), rice husk ash (RHA), and basil plant ash (BPA), have been widely documented to enhance the strength of cement blends, particularly in enhancing compressive and tensile strength, reducing porosity, and enhancing overall durability. BPA and RHA have shown remarkable performance in applications involving ultra-high-performance concrete (UHPC), in which enhanced strength and long-term durability are paramount. Their high amorphous silica content, fine particle size, and optimized thermal processing result in dense microstructures and the generation of extra calcium silicate hydrate (C-S-H) gels, resulting in enhanced mechanical interlocking and load-carrying capacity. Fly ash, although often regarded as a lower-grade industrial by-product owing to storage degradation, has renewed potential through mechanical activation techniques such as extended milling [14]. Its pozzolanic reactivity is increased by this process, which modifies the morphology of the particles and increases their surface area. When properly handled, FA becomes a competitive and feasible SCM, particularly when used in standard mortars and all-purpose concrete mixtures. In addition to strengthening, it improves the resistance to moisture intrusion, chloride penetration, and other durability-related issues [15].

One of the most important reasons for the enhanced performance of cementitious systems is the synergistic action of the pozzolanic activity and fine-grained particle size distribution in all three systems. The more robust and denser concrete matrices resulting from these advances are less susceptible to cracking, shrinking, and deterioration with time. Because of these advances, these systems are highly appropriate for use in structures exposed to harsh environmental conditions. The value of BPA, RHA, and FA in the production of high-performance, environmentally friendly concrete is likely to grow with further research on treatment methods and mix designs [16].

**Environmental and Economic Implications**

The analyzed studies put the double benefits of supplementary cementitious materials (SCMs) derived from waste into environmental sustainability and economic sustainability. Recycling waste not only aids in the recovery of precious by-products, but also considerably minimizes the utilization of traditional cement, which is energy- and carbon-intensive. Replacement of a fraction of regular Portland cement (OPC) with minerals such as basil plant ash (BPA), rice husk ash (RHA), and fly ash (FA) results in a significant reduction in carbon dioxide emissions, a pivotal move towards mitigating climate change [17]. BPA and RHA, agricultural waste products that are not sufficiently processed, are renewable and readily accessible substitutes for raw and mined materials; therefore, natural resources are conserved. FA, which is usually stored as a by-product of coal burning, offers a strategic solution to the age-old industrial waste dumping problems [18].

Economically, the use of SCMs means cost reduction through a decreased amount of cement needed and waste management costs. As most of these materials are readily available and locally extracted, their use also lowers transport costs and supports regional loops of resources in line with the provisions of a circular economy. Additionally, their incorporation into construction activities reinforces adherence to international environmental regimes and green-building codes, enhancing the sustainability credentials and market value of construction works [19]. However, for all this to be achieved at scale, additional investments are required to establish effective processing technologies, quality control systems, and standardized procedures. Scaling up SCMs adoption also requires concerted efforts among policymakers, industry actors, and researchers to address regulatory hindrances, guarantee performance consistency, and achieve public acceptance. When methodically incorporated, these innovations have the potential to transform concrete manufacturing into a more robust, cost-effective, and sustainable industry [20].

 

## CONCLUSIONS AND FUTURE DIRECTIONS

The findings of this review confirm that pozzolanic materials such as BPA, rice husk ash (RHA), and fly ash (FA) have great potential as green supplementary cementitious materials (SCMs) for use in concrete. These materials, recovered from agricultural residues and industrial by-products, impart additional environmental benefits as green alternatives to ordinary Portland cement (OPC), enhancing the durability and mechanical properties of concrete when adequately processed. Thermal activation of RHA and BPA, particularly in the temperature range around 700°C, maximizes the amount of amorphous silica, thereby increasing pozzolanic activity, lowering porosity, and dramatically improving tensile strength and compressive strength. Similarly, mechanical activation of long-stored fly ash significantly increases its surface area and reactivity, rendering it useful as an SCM, even after long-term storage. All three materials work well environmentally by decreasing landfill wastes, $CO_2$ emissions and supporting circular economy thinking. Relatively cheap in cost, they act as substitutes for valorizing waste in place of virgin raw material. The performance of these materials is, in the first place, subject to uniform treatment procedures and quality control; hence, elaboration on the importance of uniform process methodology and detailed microstructural analysis is necessary. The review further calls attention toward the need to consider the inclusion of these SCMs in existing concrete standards, as well as to investigate long-term durability.

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