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REVIEW ARTICLE

A review on the recycling and utilization of incense ash and its application in building materials

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Abstract—As a solid waste produced in vast quantities each year, incense ash poses both resource inefficiency and environmental hazards under conventional disposal practices. In recent years, its valorisation in construction materials has attracted increasing attention. This review systematically integrates existing studies on the physicochemical characteristics of incense ash, its recycling and treatment technologies, and its applications in cementitious construction materials such as cement and concrete. The reviewed literature indicates that incense ash is rich in inorganic mineral constituents and exhibits notable pozzolanic activity, enabling its use as a supplementary cementitious material to partially replace conventional raw materials. Such utilization not only enhances certain material properties but also contributes to a reduction in production costs. However, its composition is highly influenced by the source materials in different countries/regions, and potential risks such as heavy metal contamination necessitate control through pretreatment. Future efforts should focus on promoting classified collection, standardized processing, and toxicity assessment of incense ash to facilitate its large-scale application in green building materials and contribute to sustainable development.

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1. Introduction

In the context of accelerating globalisation, environmental challenges have emerged as a shared, critical concern for human society. Phenomena such as climate change, resource depletion, and ecological degradation are profoundly affecting the stability of Earth's systems and, consequently, the sustainability of socio-economic development [1]. Specifically, rapid industrialisation and urbanisation have fuelled economic growth but have also led to continuous increases in greenhouse gas emissions and a noticeable deterioration in the ecological environment [2]. How to effectively alleviate environmental pressure while safeguarding economic growth and social development has become a central issue in today's global environmental governance. Against this increasingly demanding backdrop, the 2030 Agenda for Sustainable Development, adopted by the United Nations, underscores a trinity of "economic development, social progress and environmental protection" and sets quantified control targets for sustaining development, highlighting a global consensus on the direction of green transition [3]. Concrete constitutes one of the most essential materials in civil infrastructure. Due to its unmatched versatility, inherent strength, and broad availability, it has become the most widely produced construction material globally. Cement, a major constituent of concrete, saw its annual production exceed 4.13 billion tons [4], with projections suggesting an increase to 4.68 billion tons by 2050 [5]. However, cement production carries severe environmental implications. With global output surpassing 4 billion tons, the cement industry is responsible for approximately 8% of worldwide CO_2 emissions. To align with the Paris climate targets, annual emissions from the built environment must be reduced by at least 16% by 2030 [6] - [7]. Moreover, cement production accelerates the depletion of natural resources. Consequently, reducing cement consumption and developing supplementary cementitious materials (SCMs) are crucial strategies for achieving decarbonization in the construction sector. Researchers have focused extensively on utilising various types of biomass ash and industrial by-product ashes as partial cement replacements to improve the performance of cementitious systems while reducing environmental burdens. The literature reveals diverse findings regarding their efficacy. For example, Gupta et al. demonstrated that biomass ashes derived from food and wood residues, characterised by a high carbon content (71%), can significantly improve mortar impermeability [8]. Similarly, Vu et al. [9] highlighted that biomass ash incorporation can enhance mechanical performance, durability, permeability resistance, and cost efficiency. Cerný [10] found that woody biomass ash can replace up to 30% of ordinary Portland cement without introducing significant harmful elements, thus enabling its direct application. Conversely, Kaminskas et al. [11] recommended that the replacement ratio not exceed 15%, as strength variations are strongly dependent on the hydration of calcium silicate phases. Global researchers use various cementitious materials to replace some cement in cementitious or concrete materials, such as wood ash [12], fly ash [13], rice husk ash [14], coconut husk ash [15], palm oil fuel ash [16], garbage charcoal [17], etc, to replace some cement in building materials. The recycling of alternative building materials will greatly reduce their impact on the environment and help protect the ecological environment.

Incense ash (IA) represents a major household and temple-generated waste stream in numerous Southeast Asian countries, including China, Taiwan, Thailand, and India. Incense sticks (IS) are widely consumed in temples, churches, households, and other places of worship [18]. In India, an estimated 3 to 4 million tonnes of incense sticks are consumed

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annually across religious sites and households. India is also the world's largest producer of incense sticks, with an estimated annual production of 208 billion sticks, and the industry continues to grow at around 20% per year [19] - [20]. Among Hindus in India and internationally, incense ash is traditionally regarded as sacred and is disposed of in rivers or other water bodies. However, IA is chemically complex, comprising more than 50% calcium and magnesium oxides or carbonates, 20 – 30% carbon, approximately 20% silica, and about 5% aluminium, iron, and other trace elements [19]. The leaching of alkali metals from IA can increase water alkalinity and hardness, consequently deteriorating the quality of drinking water. Furthermore, IA contains significant concentrations of heavy metals (such as Cu, Ni, Co, Cr, Mo, As, Zn, Hg, Cd, and Sr), which may further pollute soil and water ecosystems, posing substantial risks to human health and the environment [21] - [22]. In the current macro context of green development and circular economy, how to reduce the solid waste of temple incense ash or recycle it as a resource has become an urgent and systematic research topic. The main components of incense ash are silicon dioxide and calcium oxide, which have significant similarities in structure and chemical composition with commonly used auxiliary cementitious materials. This indicates that the use of incense ash as a substitute cementitious material in cement products or concrete materials has an important theoretical basis and practical feasibility. It also provides a method to alleviate the environmental pressure caused by cement production. This is also the main starting direction of our research topic on the application of replacing some cement with incense ash in building materials. Therefore, this study conducted a systematic search for peer-reviewed publications across major academic databases including Scopus, Web of Science, and Google Scholar. The search encompassed all research published up to the present date. Keywords and Boolean operators such as "incense ash," "resource recovery and utilisation," "cementitious materials," "supplementary cementitious materials," "cement replacement," and "mechanical properties" were employed to ensure a comprehensive retrieval of relevant studies. This article systematically reviews the physical and chemical properties of incense ash and the research on resource recycling, with a focus on summarising its application research progress as a substitute for some cement in building materials. Further analysis was conducted on the current research gaps and challenges, while outlining potential directions for future development.

2. Physicochemical Properties of Incense Ash

Incense is an aromatic biotic material that releases fragrant smoke upon combustion. Traditionally, its composition includes aromatic woods, herbs, resins, essential oils, and a flammable binder [23]. Incense use remains widespread in religious rituals of major faiths, as well as in meditation, aromatherapy, and even as an insect repellent [19]. Incense is marketed in various forms, including powders, coils, sticks, ropes, and papers, offering a broad range of fragrances [24]. The global incense market is currently undergoing rapid expansion, with China and India serving as the leading producers and exporters, alongside the United States and Brazil [19]. While the precise geographic origin of incense remains debated, with references pointing to China, India, and Egypt, its cultural and religious significance is thoroughly documented in ancient texts and spiritual practices worldwide [19]. Modern incense sticks are typically manufactured using wood powder, bamboo sticks, plant-based adhesives, and small amounts of chemical accelerants. Due to inherent differences in raw materials and specific formulations across regions and temples, the chemical composition of the resulting incense ash varies considerably [25].

2.1 Comparative Analysis of Incense Ash and Cement

Incense ash, produced by the combustion of temple incense, exhibits distinct physical characteristics compared with ordinary Portland cement (OPC), particularly in specific gravity, surface area, and particle morphology. In [25] - [27], OPC has a higher specific gravity (3.10–3.15 g/cm³), whereas IA is considerably lighter (2.0–2.6 g/cm³) due to its porous microstructure and residual carbonaceous matter, as summarised in Table 1. IA also typically exhibits a larger specific surface area (400–600 m²/kg or higher) than OPC (300–400 m²/kg), providing more reactive sites that may enhance mechanical performance and durability, albeit at the cost of increased water demand [28]. Moreover, unlike the relatively regular and angular particles of OPC, IA particles are irregular, flaky, and porous, often containing partially combusted residues. Such morphology lowers bulk density and influences the interfacial bonding within cementitious matrices [29].

Table 1 Typical physical properties of OPC and incense ash (IA) [25] - [27]

Property	Ordinary Portland cement	Incense ash
Specific gravity (g/cm³)	3.10 – 3.15	2.0 – 2.6
Specific surface area (m²/kg)	300 – 400	400 – 600 (or higher)
Particle morphology	Regular, angular particles	Irregular, flaky, porous; includes unburned residues

The observed similarities and discrepancies in the physical properties between incense ash and ordinary Portland cement substantiate the technical feasibility of IA as a partial supplementary cementitious material. Compared to cement, incense ash has a lower specific gravity and a larger surface area, which may help reduce its own weight and improve compactness. However, it may also pose challenges such as increased water demand, poorer flowability, and a possible decrease in early strength. Nevertheless, its incorporation necessitates meticulous optimisation of the replacement level and construction practices, with particular attention to its comparatively lower specific gravity and associated higher water demand, to mitigate any adverse effects.

2.3 Chemical Composition of Incense Ash

The chemical composition of incense ash varies substantially due to differences in raw materials, additives, and combustion conditions, resulting in pronounced regional heterogeneity. IA consists mainly of SiO_2, CaO, K_2O, MgO, Al_2O_3, and minor amounts of unburned carbonaceous residues [19]. Many studies identify IA as "high-calcium." For instance, CaO contents exceeding 40 wt.% in certain temple-derived IA samples, approaching or only slightly below that of Portland cement [27], [31] - [32], as summarised in Table 2. Such high CaO levels typically arise from calcium-rich additives (e.g., $CaCO_3$ powders, slaked lime) or high-temperature combustion that facilitates $CaCO_3$ decomposition. These ashes may actively participate in cement hydration, imparting limited cementitious potential [33]. Of course, there are also studies on IA samples that show a "silicon calcium equivalent" composition, with SiO_2 and CaO contents ranging from 30 to 40 wt.% and CaO contents lower than about 60 wt.% in ordinary Portland cement [30], [34]. This distribution is usually associated with raw materials rich in silica (such as granite, diorite, and alpha quartz) or with unintentional contamination of termite soil during the incense-burning process [35]. IA is also characterised by elevated K_2O contents (5–15 wt.%), which can increase system alkalinity and heighten the risk of alkali–silica reaction when incorporated into concrete [28]. Additionally, relatively high concentrations of heavy metals (e.g. Cu, Ni, Co, Cr, Mo, As, Zn, Hg, Cd, Sr) are frequently detected in IA, posing potential risks of soil and water contamination and associated ecological and human health hazards [19]. The chemical composition of IA can exhibit a spectrum of characteristics, ranging from "high-calcium, cement-like" to "silicon-calcium equivalent" pozzolanic types, with current research indicating a predominance of the high-calcium variety. Therefore, there are certain differences in the composition of fragrant ash from different regions and sources, and the mixing design must be formulated based on its chemical element composition. Although this unique compositional feature endows ash with the potential to serve as a supplementary cementitious material, it also presents challenges in terms of dosage control, environmental safety, and long-term durability.

Table 2. Chemical compositions of the OPC and IA or ISA in different countries

Materials	Composition (%)										Area	Literature
	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	P_2O_5	Na_2O	LOI		
OPC	66.89	19.01	4.51	3.20	0.45	1.23	2.53	-	1.10	1.13	Bangladesh	[27]
IA	47.35	12.95	6.03	1.86	3.62	3.14	5.09	-	3.77	15.20	Taiwan	[27]
ISA	31.04	39.46	8.07	0.49	0.02	0.87	-	-	-	14.60	Southeast Asia	[30]
ISA	49.60	20.36	4.77	4.28	-	3.90	8.24	3.94	-	-	India	[31]
ISA	49.20	20.55	4.78	4.29	4.45	4.00	8.23	4.50	-	-	India	[32]

LOI: Loss on ignition

Based on the above analysis of the physical and chemical properties of incense ash, "high calcium" incense ash commonly used in research has certain similarities and complementarity with ordinary Portland cement. These characteristics collectively provide a robust foundation for its potential application in construction materials. IA is characterised by low density, high specific surface area, significant compositional variability, and a porous microstructure. These combined features underscore its potential feasibility as a partial cement replacement. However, some differences in the chemical composition are also observed for IA originating from different countries/regions. For instance, the CaO content in IA from Bangladesh (66.89%) is more than twice that of Southeast Asia (31.04%). On the other hand, the SiO_2 content in IA from Southeast Asia (39.46%) is the highest among all, more than 3 times that of Taiwan (12.95%). These differences must be considered when IA is used as a supplementary cementitious material. Nevertheless, successful practical application necessitates careful source-specific characterisation and rigorous performance evaluation. Appropriate pretreatment methods (e.g., grinding, thermal activation, or alkali activation), chemical composition detection, and optimised dosage design are therefore essential to maximise its beneficial effects while effectively mitigating associated durability and environmental risks.

3. Resource Utilisation of Incense ash

Based on the physicochemical characteristics and composition of Incense ash (IA or ISA), it can be observed that IA or ISA is rich in calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and a certain amount of carbon, while also containing trace heavy metals and soluble salts. This unique composition not only poses potential environmental risks if disposed of indiscriminately, but also provides a sound theoretical basis and significant application potential for resource utilisation. Consequently, research focus in recent years has gradually shifted from "disposal" to "utilisation," exploring IA's applications in environmental remediation, metal recovery, soil improvement, and construction materials.

3.1 Environmental Remediation and Adsorbent Applications

Due to its high specific surface area, porous structure, and abundance of metal oxides (e.g., CaO, SiO_2, Al_2O_3), IA or ISA exhibits considerable adsorption potential. Wastewater treatment: Studies have shown that IA or ISA can effectively adsorb dyes, phosphates, and certain heavy metal ions (e.g., Pb^{2+}, Cd^{2+}, Cr^{6+}) from aqueous solutions, primarily through ion exchange, surface complexation, and precipitation mechanisms [36]. Gas purification: Modified IA or ISA-based materials have been investigated for the removal of SO_2 and NOx. Stabilisation of solid waste: The alkaline components in IA or ISA can immobilise or stabilise heavy metals present in other hazardous wastes [37]. Besides, IA or ISA contains recoverable metal elements such as Fe, Zn, Cu, and Pb, in addition to being rich in CaO and SiO_2, which underscores its resource recovery potential. Metal extraction: Selective recovery of Zn, Cu, and Pb can be achieved via acid leaching or roasting–leaching processes, like the utilisation of coal fly ash and metallurgical slags [38]. Magnetic separation: Gupta et al. investigated the recovery of nano iron minerals from temple incense ash using dry–wet magnetic separation, reporting that 15–25% of ferrous content can be recovered through wet magnetic separation [31].

3.2 Agricultural, Soil Improvement Applications and Construction

Incense ash (IA or ISA) is rich in essential plant nutrients such as calcium, magnesium, and potassium and exhibits alkalinity, enabling it to adjust soil pH, improve the fertility of acidic soils, and enhance overall soil structure [39]. Functioning as a nutrient source (e.g., K and Ca), it can partially substitute conventional amendments like lime and wood ash. Crucially, however, the potential accumulation of trace heavy metals (e.g., Pb, Cd, As) in soils and crops mandates careful risk assessment prior to large-scale application [40]. Due to its relatively high CaO content (sometimes exceeding 40 wt%), IA or ISA exhibits a chemical composition similar to that of Portland cement, making it a promising partial replacement material for cement, a field that has received the most extensive research attention to date. Studies have demonstrated that IA or ISA can enhance the performance of cementitious materials when used as a supplementary cementitious material. Kuo et al. [27] reported that incorporating an appropriate dosage of IA or ISA (e.g. 5%) accelerates hydration, shortens setting time, and promotes the formation of calcium silicate hydrate (C–S–H) through filler effects and pozzolanic reactions. This reduces the $Ca(OH)_2$ content, thereby improving structural compactness, mechanical strength, and thermal conductivity. Similarly, He et al. found that incorporating 5–20% IA or ISA increases hydration heat release, with 5% replacement yielding optimal results. At this dosage, the 28-day compressive strength improved by approximately 19.8%, and the pore structure was refined with an increase in high-density C–S–H phases. However, excessively high replacement levels were detrimental to strength development [30].

Investigations into the valorisation of IA have expanded across environmental remediation, metal recovery, agricultural utilisation, and construction materials, yielding a series of affirmative advances. At present, the application technology in the field of building materials is relatively mature and has gradually achieved a leap from laboratory research to engineering practice; In terms of adsorbent development and metal recovery, research is still mainly in the laboratory stage, and its large-scale application prospects need further technological optimization and economic feasibility evaluation; In terms of agricultural applications, although it has shown certain utilization value, the potential risks of long-term application to soil environment and human health still need to be systematically evaluated. Collectively, the calcium- and silica-rich character of incense ash confers pronounced similarities to supplementary cementitious materials, endowing this solid residue with notable valorisation potential. Future interdisciplinary convergence and technological innovation are anticipated to amplify its contributory role within a circular economy framework.

4. Research Progress on Incense ash in Construction Materials

In recent years, Incense ash (IA or ISA), owing to its richness in inorganic components such as calcium, silicon, and aluminium, has been increasingly explored as a partial cement replacement or supplementary cementitious material in construction applications. Experimental investigations have primarily focused on evaluating its effects on the fresh properties, mechanical performance, hydration behaviour, pore structure, and durability of cementitious systems.

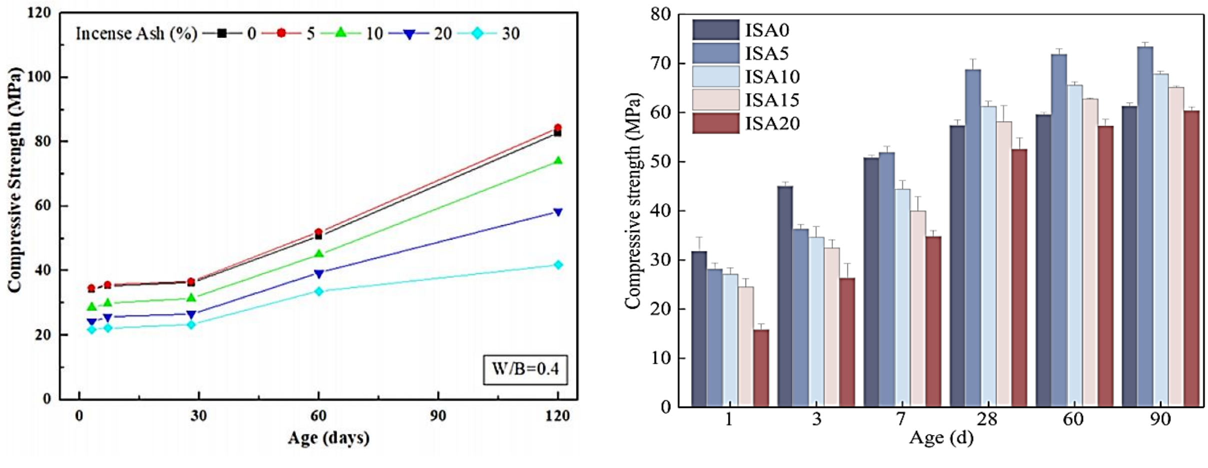

Figure 1. Compressive strength development of incense ash paste [27]

4.1 Mechanical Properties

Current research generally concurs that IA or ISA can enhance the mechanical properties of cementitious materials when employed at low replacement levels. Kuo et al. [27] incorporated 5%–20% industrial by-product (IA) to improve structural densification via filler effects and pozzolanic reactivity. Compressive strength analysis indicates that the 5% replacement ratio yields the optimal enhancement in long-term compressive strength, as shown in Figure 1. He et al. [30] further indicated that ISA at dosages of 5 – 20% can increase the 28-day compressive strength of cement pastes, with the most significant improvement (approximately 19.8% higher than the control) achieved at 5%. However, strength subsequently declined at higher dosages, thereby exhibiting an "optimal replacement ratio" phenomenon. Yadav et al. [41] - [42] additionally demonstrated that combining ISA with fly ash further improves both strength and durability, suggesting a synergistic effect between ISA and other industrial by-products.

4.2 Hydration Process, Pore Structure and Water Absorption

IA or ISA significantly influences cement hydration kinetics. Kuo et al. [27] observed that ISA shortens the setting time and accelerates hydration, with this effect being more pronounced under elevated curing temperatures (75°C), consequently promoting early strength development. Isothermal calorimetry conducted by He et al. further revealed that incorporating 5 – 20% ISA increases the cumulative heat release, which indicates its activity in stimulating early hydration. At low dosages (5%), ISA not only accelerated the reactions but also optimised the rate of generation and the distribution of the resulting hydration products [30]. Porosity characteristics are critical determinants of both strength and durability. He et al. found that low levels of ISA refine the pore size distribution, reduce capillary porosity, and decrease overall porosity, which subsequently leads to a densification effect [30]. Long-term curing studies by Kuo et al. [27] confirmed that ISA-modified samples gradually developed denser microstructures as hydration products filled the existing pores, thereby lowering water absorption and enhancing durability. The combined use of ISA with fly ash resulted in more pronounced improvements in pore structure, thus highlighting the synergistic role of ISA with other SCMs [43, 44].

4.3 Thermal Properties and Microstructure

In addition to its mechanical and durability benefits, ISA also influences the thermal behaviour of cementitious composites. Small IA additions improve thermal conductivity, an effect attributed to reduced porosity and denser structures that establish more continuous pathways for heat transfer [28]. He et al. [30] suggest that the filler effect of ISA may enhance thermal stability, thereby supporting the composite's performance under elevated temperatures. Microstructural analyses (XRD, SEM, TGA) provide further insights. Kuo et al. [27] found that IA incorporation reduces $Ca(OH)_2$ content while increasing C–S–H production, with pores gradually filled by hydration products, thereby enhancing structural compactness. He et al. [30] showed that 5% ISA significantly increases the proportion of high-density C–S–H, improving structural stability. ISA in combination with fly ash generates more secondary C–S–H phases, diversifying hydration products and increasing matrix density [41] - [42].

Overall, existing studies on the incorporation of incense ash into cement mortar indicate that a low dosage (approximately 5%) can significantly enhance the performance of cement-based materials, primarily due to its filler effect and pozzolanic reaction. However, as the replacement level increases, material performance declines compared with the control mixture. This deterioration is mainly due to the formation of large voids at higher replacement ratios, where regions previously occupied by water in the cement mortar cannot be fully filled by hydration products. These voids consequently act as defects that impair the mechanical properties of the material. Although preliminary results suggest that incense ash has potential as a supplementary cementitious material, its further application is constrained by the pronounced variability in ash composition, the lack of long-term durability data, and the absence of relevant standards and specifications. It should be noted that the replacement intervals of incense ash adopted in existing studies are relatively broad. The optimal dosage may lie within the ranges of 0–5% or 5–10%, highlighting the necessity for more refined investigations through optimised mix design. Moreover, research on the application of incense ash in concrete remains limited. Given the higher porosity of concrete, it is still unclear whether incense ash can be utilised at higher replacement levels and how such incorporation would affect the mechanical properties and durability of concrete. These uncertainties underscore the need for systematic evaluations under different environmental conditions and across various construction materials. In addition, other critical limitations include the predominance of laboratory-scale studies, the scarcity of long-term performance data, and the lack of a unified technical standard framework. Therefore, despite the considerable potential of incense ash as a supplementary cementitious material in construction applications, its large-scale engineering implementation will require more comprehensive research, long-term performance validation, and the establishment of standardised guidelines.

5. Future Research Directions

Although recent studies on the utilisation of Incense ash in construction materials have made notable progress, most findings remain limited to laboratory-scale experiments. The available evidence indicates that IA or ISA, particularly at low replacement levels, can improve mechanical strength, accelerate hydration, refine the pore structure, and promote the formation of C-S-H gels, thereby enhancing the compactness and durability of cementitious materials [30], [43]. However, significant gaps persist between laboratory findings and large-scale engineering practice, particularly in long-term performance, microstructural mechanisms, and standardisation. Future research should, therefore, concentrate on the following directions.

5.1 Optimisation of Replacement Ratios and Application Scope

Current research predominantly investigates IA replacement ratios within the 5 – 20% range, with 5% often reported as the optimal dosage for balancing performance improvements without compromising cementitious activity [27]. Systematic studies comparing different cement systems, such as ordinary Portland cement, blended cements, mortars, and concrete, remain scarce. Future work should, therefore, establish a comprehensive IA or ISA dosage–performance database under varying water-to-binder ratios, curing conditions, and binder systems. Furthermore, the suitability of ISA for advanced materials, including high-performance concrete, self-compacting concrete, and ultra-high-performance concrete, deserves further focused exploration. Statistical modelling and machine learning approaches [44] could also be effectively applied to develop predictive models linking ISA content with mechanical and durability properties, thereby providing engineers with reliable design guidance.

5.2 Long-Term Durability and Service Performance

Most studies to date concentrate on short-term properties, particularly 28-day strength [45]. However, given that the service life of construction materials spans decades, future research must prioritise the durability of ISA-blended systems. This should include investigations into carbonation resistance and chloride penetration (which are relevant to reinforcement corrosion), sulphate and acid attack resistance, freeze-thaw cycles, high-temperature stability, and long-term shrinkage and creep behaviour [30], [46]. Such comprehensive studies will provide a more realistic assessment of ISA's performance under complex service environments and ultimately ensure the safety and engineering feasibility of its applications.

5.3 Microstructural Mechanisms and Multi-Scale Analysis

Although IA has been shown to promote C-S-H gel formation and reduce portlandite content [43], its reaction mechanisms remain insufficiently explored. Future research should employ advanced characterisation techniques, such as nuclear magnetic resonance, X-ray photoelectron spectroscopy, transmission electron microscopy, Fourier-transform infrared spectroscopy (FTIR), and synchrotron-based X-ray methods, to reveal the precise role of ISA's active components in hydration processes [47]. In parallel, computational modelling approaches such as molecular dynamics (MD) simulations and phase-field models could elucidate nanoscale interactions between ISA particles and hydration products [48]. Combining these experimental and numerical methods will enable the construction of multi-scale models linking microstructural evolution to macroscopic performance.

5.4 Synergistic Effects with Other Supplementary Cementitious Materials

As IA contains both pozzolanic activity and inert properties, its independent performance is subject to certain limitations. Consequently, its synergistic potential when blended with other SCMs deserves greater attention. For instance, ISA combined with fly ash could effectively balance early- and late-age reactivity [42]; ISA-slag blends may improve long-term strength and sulphate resistance; and ISA-metakaolin or silica fume mixtures could further refine pore structures and enhance compactness [51] – [52]. Multi-component systems should be systematically studied to determine optimal blending ratios and understand underlying mechanisms, thereby supporting the development of low-carbon, high-performance composite binders.

5.5 Environmental and Sustainability Assessment

Given the large-scale generation of incense ash and its predominant disposal via landfilling or incineration, environmental risks, such as heavy metal leaching, are a serious concern. Hence, incorporating ISA into construction materials offers notable environmental advantages. However, comprehensive sustainability evaluations remain limited. Future studies should incorporate life cycle assessment (LCA) to quantitatively assess the effects of ISA utilisation on carbon emissions, energy consumption, and resource efficiency [50]. In addition, environmental risk assessments are necessary to evaluate the potential leaching of heavy metals or other hazardous elements during the service life as well as after demolition of ISA-containing materials. Based on the work by Yadav et al. [36], the residue was collected at each successive treatment and analysed by FTIR, dynamic light scattering (DLS), XRF, X-ray XRD, FESEM, and ICP-OES until the toxic heavy metals in the residue were eliminated. Furthermore, economic cost–benefit analyses comparing ISA-based systems with conventional construction materials would provide a rational basis for decision-making under different regional conditions and project scales.

5.6 Standardisation and Engineering Applications

To date, the lack of standardised processing methods and performance evaluation protocols has hindered ISA's industrial application. Future efforts must therefore concentrate on establishing clear guidelines for ISA collection, pre-treatment, particle-size control, and chemical characterisation [51]. Pilot-scale and field studies are also essential to validate ISA's performance in real construction projects, such as masonry units, precast elements, and road materials [49]. Crucially, demonstration projects and the subsequent integration into existing building codes and standards will be vital steps toward the large-scale adoption of ISA in sustainable construction.

6. Conclusions

In summary, research on the utilisation of IA in construction materials has made encouraging progress, yet several challenges must be addressed before its widespread adoption in practical applications can be realised. Its high specific surface area and volcanic ash activity provide a basis for replacing some cement. At low dosage, IA can improve the hydration process, compact the microstructure, refine pores, and enhance strength; However, its effectiveness is significantly affected by the dosage, source, and pretreatment method, and excessive use can easily lead to various performance declines. Although research on incense ash in building materials has shown promising progress, several limitations remain. Future studies should focus on optimising its dosage. The difference between cement mortar and concrete; evaluating long-term durability; elucidating microscopic mechanisms; exploring synergistic effects with other materials; analysing environmental and economic benefits; and promoting standardisation and engineering applications. It is particularly important to strengthen policy guidance and industrialisation implementation pathways, including promoting the establishment of material standards, conducting green building demonstration projects, and fostering industry-university research cooperation to verify the feasibility of scaling up. Only through interdisciplinary research and relying on clear policy frameworks and industry collaboration can the reliable application of fragrant ash in sustainable buildings be promoted, ultimately achieving its dual goals of environmental benefits and engineering value.

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Declaration of Competing Interest
The author declares no conflicts of interest.

Credit Authorship Contribution Statement
X. Jiang (Conceptualization; Methodology; Validation; Formal analysis; Data curation; Writing - original draft)
C. Bao (Formal analysis; Investigation; Resources; Software; Writing - original draft; Visualisation)
C. Tang (Methodology; Data curation; Writing - review & editing; Resources)
K.S. Lim (Investigation; Resources; Writing—review & editing; Supervision)

Availability of Data and Materials
The data supporting this study’s findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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