

Partial Replacement of Cement with Agricultural, Industrial, Marine and Natural Ashes: A Review of Thirty-Five Studies

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Abstract: The manufacture of ordinary Portland cement (OPC) is among the most carbon-intensive industrial activities on the planet, responsible for as much as 8% of anthropogenic carbon dioxide emissions once fuel combustion is counted alongside the calcination of limestone, and for the consumption of vast quantities of non-renewable raw materials. This burden has driven sustained interest in supplementary cementitious materials (SCMs), and in particular in ash residues that would otherwise be landfilled or openly burned. This review synthesises the findings of thirty-five experimental and review studies covering more than twenty distinct ash types used as partial replacements for cement, grouped into four families: agricultural and biomass ashes (rice husk, sugarcane bagasse, bamboo leaf and stem, coffee husk, corn cob, groundnut shell, coconut shell, palm oil fuel, wheat straw, cashew leaf, date palm, sawdust and wood ashes), industrial ashes (coal fly ash, Class F fly ash, coal ash, biomass bottom ash, lime-ferrochrome ash and sewage sludge ash), marine and animal-derived ashes (seashell, periwinkle shell, walnut shell and cattle bone ashes), and natural pozzolans (volcanic ash). For each family the review examines oxide chemistry against the ASTM C618 pozzolanic criteria, the optimum replacement level, and the resulting fresh, mechanical and durability behaviour. A consistent picture emerges: siliceous agricultural ashes such as rice husk ash, processed sugarcane bagasse ash and wheat straw ash behave as reactive pozzolans and can replace 10–20% of cement while maintaining or improving strength, whereas calcareous and carbon-rich ashes (coffee husk, walnut shell, cattle bone) are better restricted to below 10% or used as fillers. Across the literature the optimum replacement level clusters between 5% and 15% by mass, above which dilution of the clinker and the scarcity of calcium hydroxide for the pozzolanic reaction cause strength to decline. The review closes by identifying the principal barriers to adoption, namely feedstock variability, the energy cost of controlled calcination and grinding, and the absence of harmonised standards for non-coal ashes, and sets out priorities for future research.

Keywords: Supplementary Cementitious Materials, Pozzolanic Ash, Partial Cement Replacement, Compressive Strength, Sustainable Concrete, Agricultural Waste, Carbon Dioxide Emissions.

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I. INTRODUCTION

Concrete is the most widely used manufactured material on Earth, and Portland cement is its most expensive and most environmentally damaging ingredient. The production of one tonne of Portland cement clinker releases on the order of 0.8–0.9 tonnes of carbon dioxide, roughly half of which arises from the chemical decarbonation of limestone ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$) and the remainder from the combustion of fuels needed to sustain kiln temperatures near 1450 °C. Aggregated across global output of more than four billion tonnes per year, the process emissions of cement manufacture amount to some 4–5% of anthropogenic carbon dioxide, and the addition of

fuel-related emissions raises the industry total to as much as 8% [36]. Beyond the carbon burden, cement manufacture depletes limestone, clay and shale reserves and consumes large amounts of electrical and thermal energy. These pressures, together with the steadily rising cost of cement in developing economies, have made the partial replacement of clinker with supplementary cementitious materials (SCMs) one of the most active fields in construction materials research [2], [38].

The term covers any finely divided solid which, used alongside Portland cement, adds to the properties of the hardened concrete by hydraulic or pozzolanic action, or by

both, in the sense given by ASTM C618 [37]. The classical industrial SCMs, that is coal fly ash, ground granulated blast-furnace slag and silica fume, are by-products of thermal power generation and metallurgy, and their supply is finite and increasingly contested. As coal-fired power is retired in many regions, the availability of conventional fly ash is expected to fall, sharpening the search for alternative ashes derived from agriculture, forestry, marine processing and municipal waste streams [31], [24].

Ash is an attractive candidate for two independent reasons. First, many ashes are rich in amorphous silica or in reactive alumina, and can therefore react with the calcium hydroxide liberated during cement hydration to form additional calcium silicate hydrate (C–S–H), the phase that gives concrete its strength. Second, ashes are generated in enormous quantities as wastes whose disposal is itself an environmental problem: rice husk, sugarcane bagasse, coffee husk, palm residues and municipal sludge are routinely landfilled or burned in the open, generating particulate pollution and occupying land. Converting these residues into a cement substitute simultaneously reduces clinker demand and diverts waste from disposal, a double dividend that aligns closely with circular-economy objectives [6], [19].

The pozzolanic quality of an ash is not guaranteed by its origin, however. It depends on the mineralogy of the feedstock, the combustion temperature and atmosphere, the residence time, and the fineness to which the ash is subsequently ground. Uncontrolled open burning frequently crystallises the silica or leaves a high unburnt-carbon content, both of which suppress reactivity. Consequently the experimental literature reports a very wide range of outcomes for nominally similar materials, and the identification of an optimum replacement level for each ash, beyond which the dilution of cement outweighs the pozzolanic contribution, has become the central practical question of the field.

This review draws together thirty-five studies to provide a structured, comparative account of ash as a partial cement replacement. Its objectives are: (i) to classify the ashes examined in the source literature and place their oxide chemistry against the ASTM C618 pozzolanic criteria; (ii) to summarise, ash by ash, the optimum replacement level and the associated effect on fresh and hardened properties; (iii) to draw cross-cutting conclusions about the mechanisms that govern performance; and (iv) to identify the barriers to adoption and the priorities for further work. Unlike single-material reviews, the present synthesis is deliberately broad, allowing the reactivity of chemically contrasting ashes to be compared on a common basis.

II. SCOPE AND METHOD OF THE REVIEW

The material examined here comprises thirty-five peer-reviewed articles and conference papers, each concerned with the partial replacement of Portland cement by an ash in mortar or concrete. The studies span publication years from 2010 to 2023 and originate from research groups in Africa, South and East Asia, the Middle East, Europe and the Caribbean, giving the synthesis a broad geographic base. Three of the sources

are themselves review articles, one on rice husk ash [2] and two on seashell ash [31], [32], and their aggregated findings are used to corroborate the primary experimental studies.

For every study the following information was extracted where reported: the oxide composition of the ash (principally SiO_2 , Al_2O_3 , Fe_2O_3 and CaO , together with the loss on ignition), the specific gravity and fineness, the range of replacement levels investigated, the mix proportions and curing regime, and the measured effect on workability, setting time, compressive strength and, where available, split-tensile strength, flexural strength and durability indicators such as water absorption and permeability. The single figure of greatest practical interest, the optimum replacement level, was recorded for each ash; it is defined throughout as the highest replacement percentage at which the principal target property (usually 28-day compressive strength) is maintained at or above that of the control, or, where no mix exceeds the control, the level giving the smallest acceptable loss.

Because the source studies differ in cement grade, mix ratio, water–binder ratio, aggregate type and calcination protocol, their absolute strength values are not directly comparable. The review therefore emphasises relative behaviour, that is the direction and magnitude of change against each study's own control, and the position of the optimum, rather than ranking ashes by raw strength. This is the appropriate basis for comparison given the heterogeneity of the underlying experiments.

III. CLASSIFICATION AND POZZOLANIC CHEMISTRY OF ASHES

➤ A Four-Family Classification

The ashes covered by the source literature fall naturally into four families defined by their origin and dominant chemistry.

Agricultural and biomass ashes are the products of burning crop and forestry residues. This is by far the largest family in the literature and includes rice husk ash, sugarcane bagasse ash, bamboo leaf and bamboo stem ashes, coffee husk ash, corn cob ash, groundnut shell ash, coconut shell ash, palm oil fuel ash, wheat straw ash, cashew leaf ash, date palm ash, sawdust ash and wood ash. Their chemistry is bimodal: residues with a high biogenic-silica content, such as rice husk and wheat straw, yield strongly siliceous ashes, whereas leaf, wood and husk residues rich in plant nutrients yield ashes with a substantial calcium and potassium content.

Industrial ashes are by-products of combustion and metallurgical processes. They include coal fly ash and its Class F fraction, general coal ash, biomass bottom ash from power generation, the ferrochrome ash captured in the gas-cleaning plant of a ferro-alloy furnace, and sewage sludge ash from the incineration of wastewater residues. This family contains the established SCMs and generally displays the most consistent pozzolanic behaviour.

Marine and animal-derived ashes are dominated by calcium carbonate in the raw state, which converts to calcium

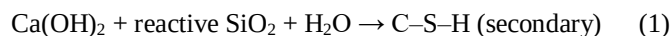
oxide on calcination. Seashell ash, periwinkle shell ash, walnut shell ash and cattle bone ash belong here. Because these materials are calcareous rather than siliceous, they act more as reactive fillers and sources of lime than as classical pozzolans.

Natural pozzolans, represented in this literature by volcanic ash, are pyroclastic materials whose glassy aluminosilicate content confers pozzolanic activity without any processing beyond grinding. They are the historical antecedent of all modern SCMs, having been used in Roman concrete.

➤ The Pozzolanic Reaction and the Role of Oxide Chemistry

The hydration of Portland cement produces calcium silicate hydrate (C–S–H) and, as a by-product, calcium hydroxide (portlandite, Ca(OH)_2), which contributes little to strength and is vulnerable to leaching and acid attack. A

pozzolan, in the sense ASTM C618 [37] gives the term, is a material carrying silica, or silica and alumina together, which in the presence of moisture takes up that calcium hydroxide and yields further C–S–H, as shown in (1).



This secondary reaction, illustrated in Fig. 1, densifies the microstructure, refines the pore network, consumes the vulnerable portlandite, and improves both strength and durability. Its extent is governed by the quantity of reactive (amorphous) silica and alumina available, by the fineness of the ash, and by the supply of calcium hydroxide, which is itself reduced as more cement is replaced. This last point explains why every ash has an optimum: as replacement rises, the additional reactive silica eventually outstrips the diminishing portlandite, leaving unreacted ash that merely dilutes the binder and lowers strength [18], [10].

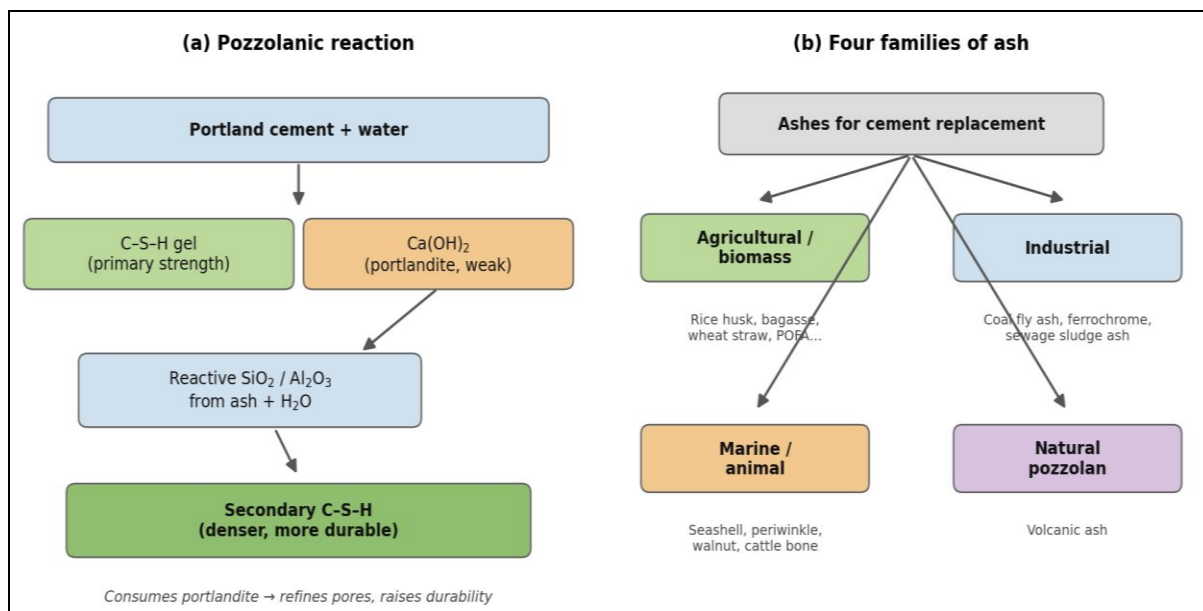


Fig 1 Schematic of the pozzolanic mechanism (a) and the four-family classification of ashes used as partial cement replacements (b). The reactive silica and alumina supplied by an ash consume the weak portlandite liberated by cement hydration to form additional, denser calcium silicate hydrate.

➤ The ASTM C618 Criterion

The most widely applied benchmark for pozzolanic suitability is ASTM C618, which classifies coal fly ash and natural pozzolans and sets a minimum combined content of the three acidic oxides, $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ (abbreviated SAF throughout this review). It is important to be precise about the current requirement, because the specification has changed. In the present edition the SAF minimum is 70% for Class N natural pozzolans and 50% for the coal-derived Classes F and C; editions prior to 2019 applied the 70% limit to Class F as well, and it is that historical 70% threshold that the great majority of the source studies reviewed here adopt as

their pass/fail test. The specification also limits the loss on ignition, to 10% for Class N and 6% for Classes F and C, with a provision permitting Class F up to 12% where acceptable performance records or laboratory testing support it [37]. Because almost all of the ashes reviewed here are non-coal materials closest in character to Class N, the 70% criterion is retained throughout as the comparative benchmark, and it provides a convenient organising axis for the discussion that follows. Table 1 and Fig. 2 summarise the oxide chemistry of the principal ashes against this criterion, and Fig. 3 maps them by silica and calcium content.

Table 1 Representative Oxide Composition (% by Mass) and Pozzolanic Classification of the Principal Ashes Reviewed

Ash type	SiO_2	Al_2O_3	Fe_2O_3	CaO	LOI	SAF	Character	Ref.
Rice husk ash	75.0	1.29	0.78	3.3	3.67	77.1	Siliceous pozzolan	[1]
Sugarcane bagasse ash	71.5	4.70	2.1	3.2	n.r.	78.3	Siliceous pozzolan	[5]
Processed bagasse ash	66.7	9.24	1.53	10.07	1.9	77.5	Siliceous pozzolan	[6]

Bamboo leaf ash	65.66	n.r.	n.r.	15.22	n.r.	76.35 ^a	Siliceous pozzolan	[7]
Bamboo stem ash	57.7–68.7	0.15–6.66	0.16–3.22	4.15–11.9	0.17–0.42	>70	Siliceous pozzolan	[8]
Coffee husk ash	n.r.	n.r.	n.r.	45–65	27.98	37.1 ^a	Calcareous, carbon-rich	[9], [10]
Corn cob ash	n.r.	n.r.	n.r.	n.r.	n.r.	<70	Weak pozzolan	[11]
Groundnut shell ash	24.32	5.31	1.01	8.93	n.r.	30.6	Poor pozzolan	[12]
Coconut shell ash	37.97	24.12	15.48	4.98	11.94	77.6	Siliceous-aluminous	[13], [14]
Palm oil fuel ash	53.52	11.40	12.68	4.62	4.83	77.6	Siliceous pozzolan	[15], [16]
Wheat straw ash	67.34	6.44	4.36	10.60	n.r.	78.1	Siliceous pozzolan	[17]
Cashew leaf ash	56.82	6.08	1.62	8.34	5.32	64.5	Marginal pozzolan	[18]
Sawdust ash	65.30	4.0	2.23	9.6	n.r.	71.5	Siliceous pozzolan	[20]
Wood ash	20.55	3.09	1.43	47.60	n.r.	25.1	Calcareous	[21], [22]
Walnut shell ash	18.98	4.17	2.59	63.27	6.37	25.7	Calcareous filler	[23]
Coal ash (fly)	69.85	18.74	2.20	2.74	2.40	90.8	Class F pozzolan	[27]
Biomass bottom ash	22.1	4.2	3.9	62.1	n.r.	30.2	Calcareous	[28]
Seashell ash	1.6–27	0.14–8.8	0.05–4.8	51.6–87.2	40–43 ^b	<30	Calcareous filler	[31], [32]
Periwinkle shell ash	32.68	10.24	7.00	26–40	n.r.	49.9	Calcareous-siliceous	[34]
Cattle bone ash	22.82	5.41	3.37	66.32	high	31.6	Calcareous (phosphatic)	[35]
Volcanic ash	32.10	18.60	24.10	2.30	14.20	74.8	Natural pozzolan	[33]
Sewage sludge ash	n.r.	n.r.	n.r.	n.r.	n.r.	variable	Variable pozzolan	[30]
OPC (reference)	20.7	5.75	2.5	64.0	1.05	29.0	Hydraulic binder	[1]

n.r. = not reported in the source study. $SAF = SiO_2 + Al_2O_3 + Fe_2O_3$ and is computed from the tabulated oxides except where marked. ^aSAF as reported in the source study; the individual oxides were not all given. ^bLoss on ignition of the raw, uncalcined shell, which reflects the carbon dioxide released when calcium carbonate decomposes on burning.

Two features of Table I deserve emphasis. First, the siliceous agricultural ashes (rice husk, both bagasse ashes, wheat straw, palm oil fuel, sawdust, bamboo) and the coal-derived ashes approach or exceed the 70% SAF threshold, marking them as genuine pozzolans. Second, the calcareous ashes (wood, walnut shell, seashell, cattle bone, biomass

bottom) sit far below the threshold because their dominant oxide is CaO rather than SiO_2 ; these materials resemble the raw meal of cement more than a pozzolan, and their value in blended cements comes from filler action, nucleation and, in some cases, a mild hydraulic contribution rather than from a strong pozzolanic reaction.

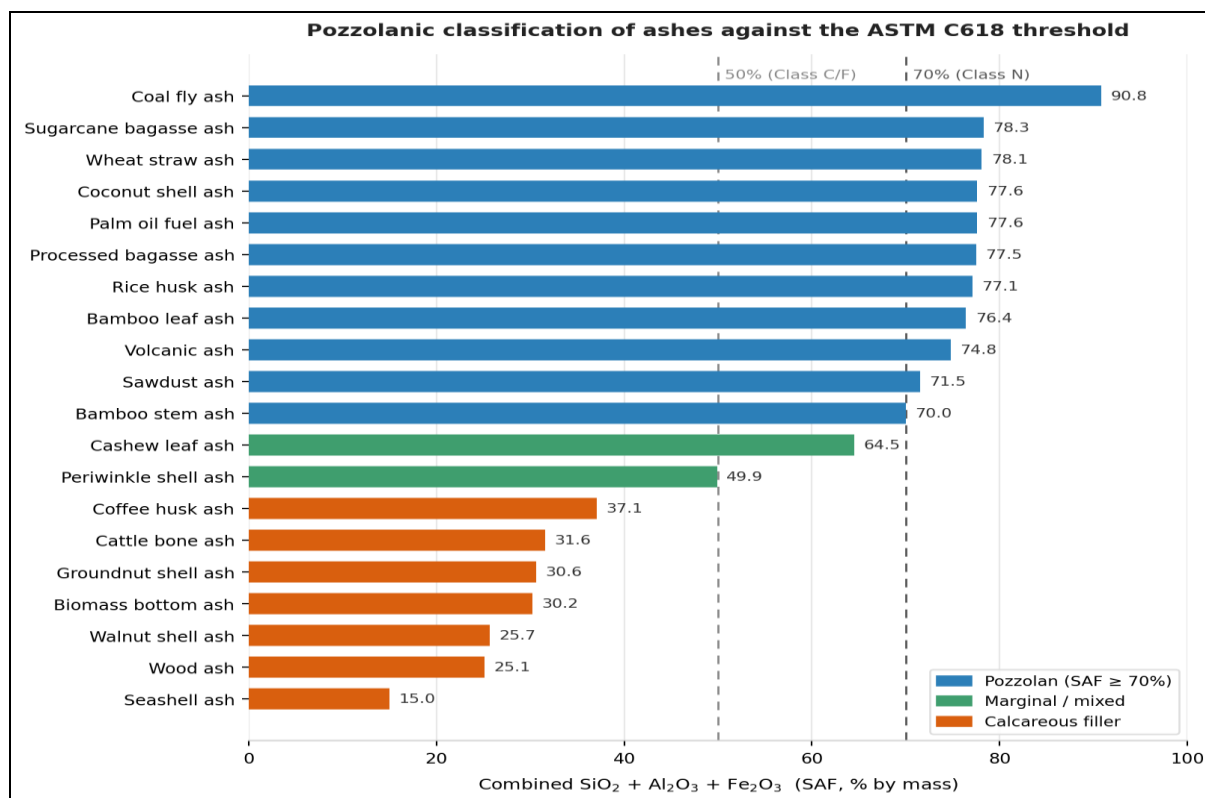


Fig 2 Combined $SiO_2 + Al_2O_3 + Fe_2O_3$ (SAF) content of the reviewed ashes against the ASTM C618 thresholds. Siliceous agricultural and coal-derived ashes approach or clear the 70% limit applied to Class N pozzolans, while the calcareous marine, animal and wood ashes fall well below it. Values from Table 1.

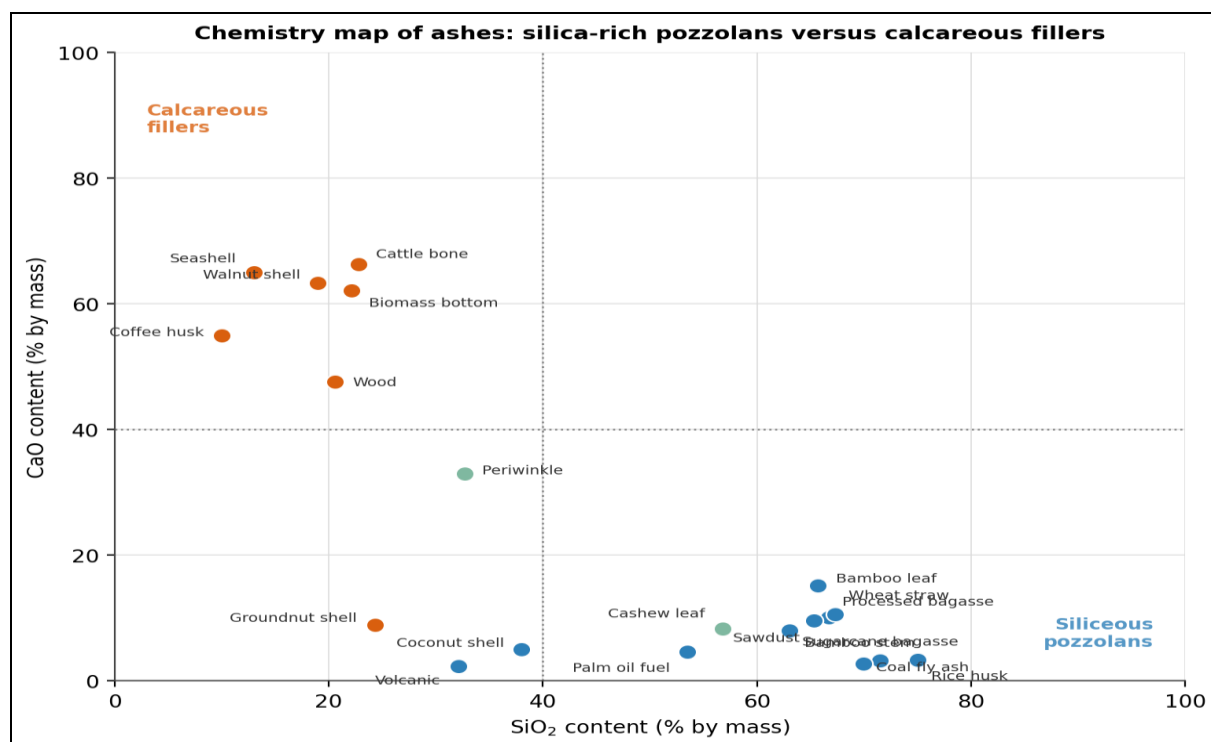


Fig 3 Chemistry map of the reviewed ashes plotted by SiO₂ and CaO content. The two populations separate cleanly into silica-rich pozzolans (lower right) and calcium-rich fillers (upper left), with a small group of mixed calcareous-siliceous ashes between them. Values from Table 1.

IV. AGRICULTURAL AND BIOMASS ASHES

➤ Rice Husk Ash

Rice husk ash (RHA) is the most extensively studied agricultural pozzolan, and four of the source studies address it directly [1], [2], [3], [4]. Rice husk contains 15–20% silica by dry mass, and controlled combustion at 500–700 °C for a few hours yields an ash whose silica is largely amorphous; Marthong reported an RHA containing 75.0% SiO₂ with a combined SAF of 77.1%, comfortably above the 70% minimum, and noted that well-burnt husk can reach 90–95% SiO₂ [1]. The specific gravity of RHA is low, near 2.4–2.5 against 3.14 for cement, and its very high specific surface area makes it markedly water-demanding.

The mechanical evidence is consistent. Marthong found that replacement up to 10% produced strength development comparable with the control and that water absorption remained acceptable up to 20% [1]. The review by Fapohunda and colleagues, aggregating a large body of experimental work, concluded that up to 10% cement replacement with RHA yields strength comparable to the control, that reactivity rises with amorphousness and fineness, and that the ash must be ground to a high specific surface area to be effective [2]. Bhushan and co-workers, working with M20 concrete, obtained maximum strength at 10% replacement, an almost equivalent result at 15%, and a useful cost reduction of about 3% [3]. Obilade, by contrast, observed that both the compacting factor and the compressive strength fell monotonically with increasing RHA, underlining that poorly processed ash behaves as a diluent rather than a pozzolan [4]. Taken together the RHA literature places the practical

optimum at 10%, extending toward 15–20% where the ash is finely ground and well burnt.

➤ Sugarcane Bagasse Ash

Sugarcane bagasse is the fibrous residue left after juice extraction; when burnt for power generation in sugar mills it produces sugarcane bagasse ash (SCBA). Kiran and Siva Kishore characterised an SCBA with 71.5% SiO₂ and reported that cement could be replaced up to 15% by mass without any major loss of strength, with the maximum strength occurring at that level [5]. The most rigorous of the bagasse studies is that of Memon and colleagues, who processed the raw ash by sieving and controlled grinding to raise its fineness and then quantified its reactivity by the Chapelle test [6]. The processed ash showed a Chapelle activity of 1293.9 mg CaO per gram, some 2.9 times the 330 mg/g benchmark for a reactive pozzolan, and a mix containing 10% processed SCBA matched or exceeded the control at all ages while improving durability. The bagasse literature therefore supports an optimum in the 10–15% range and demonstrates that simple beneficiation (sieving and grinding) can substantially raise reactivity.

➤ Bamboo Leaf and Bamboo Stem Ashes

Bamboo residues yield two distinct ashes. Bamboo leaf ash (BLA), studied by Abebaw and colleagues, had a combined SAF of 76.35% with 65.66% SiO₂ and 15.22% CaO; the additional calcium promoted the formation of calcium silicate, and 10% replacement gave the best performance, with strength declining at 15% and 20% [7]. Bamboo stem ash was examined by Rodier and co-workers specifically for its pozzolanic activity, measured through the Chapelle index and the strength activity index [8]. The stem

ashes were composed mainly of amorphous silica, returned Chapelle indices of 345–352 mg CaO per gram, above the reactivity threshold, and met the ASTM C618 strength activity requirement, confirming bamboo ash as a viable pozzolan whose exact chemistry depends strongly on burning conditions.

➤ *Coffee Husk Ash*

Coffee husk ash (CHA) illustrates the limits of the agricultural family. Two studies examined it [9], [10]. In contrast to the siliceous residues, CHA is comparatively poor in silica and rich in calcium and unburnt carbon: Gedefaw and colleagues reported a combined SAF of only 37.1%, well below any of the ASTM C618 minima, and a loss on ignition of 27.98%, far above any specification limit [10]. Despite this, both studies found that concrete satisfied its design strength up to a 10% replacement level, beyond which strength fell sharply because of the low reactive-silica content and the diluting effect of the carbon. Demissew and colleagues similarly identified 10% as the optimum for C-25 concrete [9]. Coffee husk ash is therefore best regarded as a low-level replacement whose benefit is as much in waste diversion as in strength.

➤ *Corn Cob, Groundnut Shell and Coconut Shell Ashes*

These three shell and cob residues span the reactivity spectrum. Corn cob ash (maize cob ash) was found by Tiza to have a low specific gravity of 2.55 and to function as a weak pozzolan, with 10% identified as the recommended optimum for cement replacement [11]. Groundnut shell ash is more clearly deficient: Mujedu and Adebara measured a combined SAF of only 30.64%, far below the 70% benchmark, and concluded that the ash is not a good pozzolan; it lowered concrete density and, although up to 15% replacement was tentatively recommended, strength fell with increasing content [12]. Coconut shell ash (CSA) is the most reactive of the three, with Nagarajan and colleagues reporting an unusually aluminous composition (37.97% SiO₂, 24.12% Al₂O₃, 15.48% Fe₂O₃, SAF 77.6%) that satisfies ASTM C618, and Utsev and Taku recommending 10–15% replacement for both heavyweight and lightweight concrete [13], [14]. A common observation across the shell ashes is that setting time lengthens as replacement rises, reflecting the slower pozzolanic reaction relative to clinker hydration.

➤ *Palm Oil Fuel Ash*

Palm oil fuel ash (POFA), the residue from burning palm kernel shells and fibre for energy in palm-oil mills, is a well-established regional pozzolan. Oyejobi and colleagues reported a POFA with 53.52% SiO₂ and a combined SAF of 77.6%, and found an optimum compressive strength of 23.77 N/mm² at 10% replacement, with usable performance up to 30% accompanied by a gradual strength fall [15]. Aiswarya and co-workers, working with M40 concrete, likewise identified 10% as the level giving the best compressive, flexural and split-tensile strength [16]. The consistency of the two independent studies places the POFA optimum firmly at 10%.

➤ *Wheat Straw Ash*

Wheat straw ash (WSA) is one of the clearer success stories in the agricultural family. Bheel and colleagues characterised a WSA with 67.34% SiO₂ (SAF 78.1%) and found that 10% replacement was optimum, delivering concrete that was 12% stronger in compression, 10% stronger in split tension and 11% stronger in flexure than the control [17]. The high surface area and absorptivity of the ash reduced slump as its content rose, so that the strength gain was accompanied by a workability penalty that would need to be managed with water-reducing admixtures in practice. The result confirms that a finely divided, genuinely siliceous straw ash can improve rather than merely maintain strength at modest replacement.

➤ *Cashew Leaf, Date Palm, Sawdust and Wood Ashes*

The remaining agricultural ashes cover a range of behaviours. Cashew leaf ash (CLA), studied by Kareem and colleagues, had 56.82% SiO₂ but a combined SAF of 64.5%, marginally below the pozzolanic benchmark; the optimum substitution was found to be 5%, at which the mix remained within permissible limits, while workability was acceptable up to 15% and higher additions caused porosity and strength loss as the available calcium hydroxide became insufficient to react with the added silica [18]. Date palm ash (DPA) was examined principally from an environmental standpoint by Blaisi, who showed that its trace-metal leaching lay below hazardous-waste thresholds (only arsenic was marginally elevated) and recommended beneficial use up to 10% replacement [19]. Sawdust ash (SDA), studied by Malik and colleagues, had a combined SAF of 71.5% and was found to be permissible up to 10% replacement in M25 concrete for a particle size around 90 µm, with strength and workability both declining beyond that level [20]. Wood ash (WA), examined in two studies by Hamid and Rafiq, is calcareous rather than siliceous (SiO₂ around 20%, CaO around 47%); 10% replacement gave the highest strength but the authors recommended it only marginally, cautioning that replacement above 20% falls below standard because of the low reactive-silica content and expansive tendencies [21], [22].

V. INDUSTRIAL ASHES

➤ *Coal Fly Ash and Class F Fly Ash*

Coal fly ash remains the reference SCM against which the alternative ashes are implicitly measured. Sabarish and colleagues examined general fly ash at replacement levels from 0 to 40% and found that strength was largely maintained, with 7-day strength rising from 38.5 to 43 N/mm² and 28-day strength essentially unchanged at 52–53 N/mm² for the blended mixes, confirming the well-known ability of fly ash to sustain strength at substantial replacement when adequately cured [25]. Christy and Tensing studied a Class F fly ash in mortars of three richnesses (1:3, 1:4.5 and 1:6) at replacements up to 30%, and reported that the leaner 1:6 mortar gave the optimum compressive strength and that around 20% fly ash was optimal for the replacement of fine aggregate, with the reactive silica consuming the calcium hydroxide produced during hydration [26]. Coal ash more generally was examined by Ibeto and colleagues, who replaced both cement and sand at 10–40% and found that ash

used as a sand replacement gave better slump and strength than the same ash used as a cement replacement; setting time lengthened as ash content rose, and a carbon-emission simulation confirmed the environmental benefit of the substitution [27]. The coal-derived ashes, with combined SAF values around 90%, are the most reliable pozzolans in the review.

➤ *Biomass Bottom Ash*

Biomass bottom ash, the coarser residue that collects at the base of biomass-fired boilers, was studied by Nasr and colleagues in combination with sanitary ceramic waste [28]. The ash was calcareous (CaO 62.1%, SiO₂ 22.1%) rather than pozzolanic, and compressive strength increased up to 15% replacement before decreasing with further substitution. The study is a useful reminder that biomass ash is not a single material: bottom ash and fly ash from the same boiler differ greatly, and the coarser, more calcareous bottom fraction behaves quite differently from the fine siliceous fly fraction.

➤ *Lime and Ferrochrome Ash*

The ferrochrome ash captured in the gas-cleaning plant of a ferro-alloy furnace is an unusual industrial by-product examined in detail by Acharya and Patro [29]. Rich in silica and alumina, the ash is pozzolanic but of the high-lime, weakly self-cementing type. The key finding was that when 7% lime was added to activate the pozzolanic reaction, up to 40% of the cement could be replaced by ferrochrome ash without sacrificing strength, and the strength of the control concrete was matched at a replacement as high as 47%. Ultrasonic pulse velocity and permeability, both durability indicators, improved up to about 25% replacement, and all mixes achieved pulse velocities above 4500 m/s, a mark of excellent quality. The study demonstrates that chemical activation with a modest lime addition can push the usable replacement level far beyond the 10–15% typical of unactivated agricultural ashes.

➤ *Sewage Sludge Ash*

Sewage sludge ash (SSA), the residue from incinerating the solids of wastewater treatment, addresses a growing disposal problem, since sludge laden with heavy metals is no longer acceptable as fertiliser. Doh and colleagues found that a 5% SSA replacement produced lower water absorption and increased compressive strength by up to 10% relative to the control, but that higher replacements raised absorption and reduced durability [30]. The dominant oxides (SiO₂, CaO, Al₂O₃, with significant P₂O₅) give SSA a variable and feedstock-dependent reactivity, and the heavy-metal content requires that leaching be verified before use. SSA is therefore a low-level replacement whose principal merit is the safe immobilisation of a hazardous waste within the concrete matrix.

➤ *Plant Solid Waste Ash*

Okwadha compared three plant-derived ashes, sawdust ash, maize cob ash and sugarcane bagasse ash, on a common experimental basis [24]. All three exceeded the 70% SAF benchmark (75.4%, 77.6% and 80.2% respectively), confirming their pozzolanic character. Compressive strength rose to an optimum and then fell as replacement increased,

with the optimum at 10% for sawdust and maize cob ashes and at 25% for the more reactive bagasse ash, at which the strengths were 26.3, 27.7 and 49.6 N/mm² respectively. The study is valuable because it applies a single method to several ashes, isolating the effect of feedstock chemistry from the experimental noise that complicates cross-study comparison.

VI. MARINE AND ANIMAL-DERIVED ASHES

➤ *Seashell Ash*

Seashell ash, produced by calcining the discarded shells of clams, cockles, oysters, mussels, snails and periwinkles, is dominated by calcium: the raw calcium carbonate converts to calcium oxide on burning above about 600 °C, and reported CaO contents reach 51–87% [31], [32]. Because the silica content is low, seashell ash is a calcareous filler and lime source rather than a pozzolan. The two review studies agree that the optimum replacement is low, typically 4–5%, at which the fine shell particles interlock and densify the matrix; Tayeh and colleagues noted strength gains up to 47% at early ages in some mixes at low replacement, with a definite optimum beyond which the dilution of the clinker dominates [31]. Seashell ash thus offers a route to valorise a coastal waste at modest replacement while contributing lime to the system.

➤ *Periwinkle Shell Ash*

Periwinkle shell ash, a specific marine residue abundant in the riverine areas of West Africa, was assessed by Offiong and Akpan for its physico-chemical suitability [34]. Calcination at 800 °C gave the best combination of fineness, chemical composition and 28-day strength activity; the ash calcined at 800 °C and above met the ASTM C618 loss-on-ignition requirement, and its mixed calcareous–siliceous chemistry (around 33% SiO₂ and 26–40% CaO) allowed it to serve as a partial cement replacement at low levels. The study underlines the decisive influence of calcination temperature on the usefulness of shell ashes.

➤ *Walnut Shell Ash*

Walnut shell ash, examined by Shebli, Khatib and Elkordi in cement paste and mortar, is another calcareous residue (CaO 63.27%, SiO₂ 18.98%, SAF only 25.7%) [23]. Its high calcium and low silica place it firmly outside the pozzolanic class; it acts as a fine filler and lime source, and the study treats it as a low-level replacement whose interest lies in the beneficial use of an agricultural-processing waste rather than in any strong pozzolanic contribution.

➤ *Cattle Bone Ash*

Cattle bone ash, the calcined residue of slaughterhouse bone waste, was studied by Getahun and Mitikie [35]. The ash is calcareous and phosphatic, with 66.32% CaO, a very low silica content and a significant P₂O₅ fraction. The phosphate lengthened the setting time, and although strength rose modestly up to about 10% replacement, the low silica meant that the ash contributed little pozzolanic C–S–H. The authors identified an optimum near 10% and framed the work primarily as a means of valorising an abundant abattoir waste. Bone ash is representative of the animal-derived calcareous

ashes: useful at low replacement, valuable for waste management, but not a substitute for a siliceous pozzolan.

➤ *Natural Pozzolans: Volcanic Ash*

Volcanic ash is the historical archetype of the pozzolan, its name deriving from the deposits at Pozzuoli used in Roman concrete. Abdulazeed and colleagues studied a Nigerian volcanic ash with a combined SAF of 74.8% (32.1% SiO₂, 18.6% Al₂O₃, 24.1% Fe₂O₃) and a loss on ignition of 14.2% [33]. Replacement levels of 5, 10, 15 and 20% were tested, and 20% was found to give the optimum strength, a higher optimum than most agricultural ashes because the glassy aluminosilicate of volcanic ash is intrinsically reactive and requires no combustion processing beyond grinding. The relatively high iron content and loss on ignition, the latter exceeding the 10% limit that ASTM C618 sets for Class N pozzolans, suggest that finer grinding and beneficiation could raise performance further. As a naturally occurring, abundant and unprocessed pozzolan, volcanic ash is attractive wherever pyroclastic deposits are geologically available.

➤ *Effect on Fresh-State Properties*

Across the reviewed studies a recurrent fresh-state signature accompanies ash replacement. Workability, measured by slump or compacting factor, almost always decreases as ash content rises. The cause is the high specific surface area and, for many agricultural ashes, the porous and absorptive particle morphology, which raise the water demand of the mix. Bheel and colleagues recorded a clear slump reduction with increasing wheat straw ash [17]; Obilade observed a falling compacting factor with rice husk ash [4];

and the coconut, groundnut and sawdust ash studies all reported the same trend [12], [13], [20]. The practical corollary is that ash-blended concretes generally require a water-reducing or superplasticising admixture to hold workability constant, and that comparisons made at fixed water–binder ratio understate the workability penalty.

Setting time generally lengthens with ash replacement. The slower pozzolanic reaction, the dilution of the clinker that provides the early hydration products, and, in specific cases such as cattle bone ash, the retarding effect of phosphate, all delay both initial and final set [35], [27]. A moderate retardation is often beneficial in hot climates and for large pours, but excessive retardation at high replacement can slow construction. The coal ash study by Ibeto and colleagues is notable for showing that the same ash used to replace sand rather than cement gave better slump and strength, a reminder that the mode of substitution matters as much as the ash itself [27].

VII. EFFECT ON MECHANICAL PROPERTIES

➤ *The Optimum Replacement Level*

The single most robust generalisation of the entire literature is that compressive strength rises (or is maintained) up to an optimum replacement level and then declines. Table II collects the optimum levels reported across the reviewed studies. The optima cluster tightly: as Fig. 4 shows, the great majority lie between 5% and 15%, with the reactive coal and activated industrial ashes extending higher.

Table 2 Reported Optimum Cement-Replacement Levels and Principal Mechanical Outcome for the Reviewed Ashes

Ash	Optimum replacement	Principal mechanical outcome	Ref.
Rice husk ash	10% (up to 15–20% if finely ground)	Strength comparable to control; cost saving ~3%	[1], [2], [3]
Sugarcane bagasse ash	10–15%	No major strength loss; matches control at 10% (processed)	[5], [6]
Bamboo leaf ash	10%	Best strength at 10%; declines at 15–20%	[7]
Bamboo stem ash	not determined	Reactive silica; passes ASTM C618 strength activity index	[8]
Coffee husk ash	10%	Meets design strength to 10%; sharp fall beyond	[9], [10]
Corn cob ash	10%	Weak pozzolan; 10% recommended	[11]
Groundnut shell ash	≤15% (poor pozzolan)	Strength and density fall with content	[12]
Coconut shell ash	10–15%	Meets ASTM C618; setting time lengthens	[13], [14]
Palm oil fuel ash	10%	Peak ~23.8 N/mm ² at 10%; usable to 30%	[15], [16]
Wheat straw ash	10%	+12% compressive, +10% tensile, +11% flexural	[17]
Cashew leaf ash	5%	Optimum at 5%; workability acceptable to 15%	[18]
Date palm ash	10%	Environmentally safe; usable to 10%	[19]
Sawdust ash	10%	Permissible to 10% at ~90 µm particle size	[20]
Wood ash	10% (≤20%)	Highest at 10%; marginal recommendation	[21], [22]
Coal / fly ash	20–40%	Strength maintained; 20% optimum for fine-aggregate replacement	[25], [26], [27]
Biomass bottom ash	15%	Strength rises to 15% then declines	[28]
Lime + ferrochrome ash	40–47% (with 7% lime)	Control strength matched at 47%; durability improved to 25%	[29]
Sewage sludge ash	5%	+10% strength, lower absorption at 5%	[30]
Plant solid waste ash	10% (SDA/MCA), 25% (SCBA)	Optima 26.3 / 27.7 / 49.6 N/mm ²	[24]
Seashell ash	4–5%	Filler densification; low optimum	[31], [32]
Periwinkle shell ash	low (calcine at 800 °C)	Meets LOI limit; low-level replacement	[34]
Walnut shell ash	low	Calcareous filler	[23]

Cattle bone ash	10%	Modest gain to 10%; retarded set	[35]
Volcanic ash	20%	Optimum strength at 20%	[33]

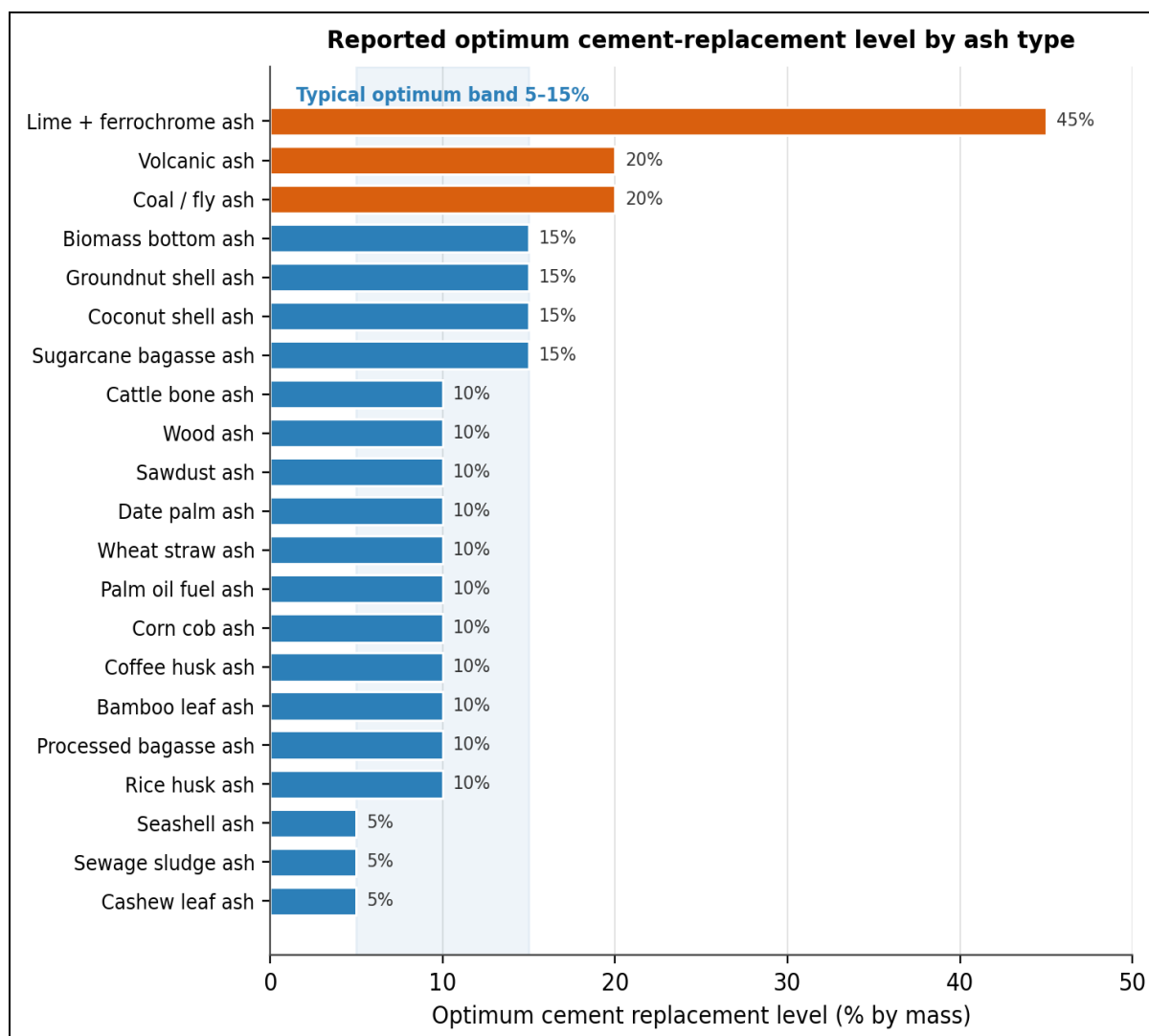


Fig 4 Reported Optimum Cement-Replacement Level for Each Ash. The Great Majority Cluster within the 5–15% Band (Shaded); Only the Reactive Coal And Volcanic Ashes and the Lime-Activated Ferrochrome Ash Extend Higher. Values from Table 2.

➤ Strength Development and Curing

Because the pozzolanic reaction is slower than clinker hydration, ash-blended concretes typically show lower early strength but continued strength gain at later ages. Several studies report that mixes that trail the control at 7 and 28 days approach or overtake it by 56 or 90 days as the secondary C–S–H accumulates [2], [6], [31]. Prolonged moist curing is therefore especially important for ash concretes, and studies that terminate testing at 28 days may understate the ultimate performance of the more slowly reacting ashes.

➤ Tensile and Flexural Behaviour

Where split-tensile and flexural strengths were measured, they broadly tracked the compressive strength: gains at the optimum and losses beyond it. The wheat straw ash study is the clearest, with simultaneous improvements of 12%, 10% and 11% in compressive, tensile and flexural strength at 10% replacement [17]; the palm oil fuel ash studies reported peak flexural and split-tensile strength at the same 10% optimum as compression [16]. This parallelism reflects

the common origin of all three strengths in the density and integrity of the C–S–H matrix and the paste–aggregate interfacial transition zone, both of which the pozzolanic reaction refines.

➤ Effect on Durability

Durability, rather than strength, is often where pozzolanic ashes deliver their greatest advantage, because the secondary reaction refines the pore structure and consumes the leachable portlandite. Several of the reviewed studies quantified durability directly. Malik and colleagues measured water absorption of sawdust-ash concrete and confirmed acceptable performance up to 10% replacement [20]. Doh and colleagues found that 5% sewage sludge ash lowered water absorption relative to the control, indicating a denser matrix, although higher replacements reversed the benefit [30]. Marthong reported that the water absorption of rice husk ash concrete remained within acceptable limits up to 20% replacement [1]. The most complete durability data set is that of Acharya and Patro, who showed that ultrasonic pulse

velocity and permeability of lime–ferrochrome-ash concrete improved up to about 25% replacement, with all mixes exceeding the 4500 m/s pulse-velocity mark that denotes excellent quality [29]. Memon and colleagues likewise reported improved durability for processed bagasse-ash concrete at the 10% optimum [6].

The mechanism is common to all reactive ashes: pore refinement lowers the permeability that governs the ingress of water, chloride and sulfate, while the conversion of portlandite to C–S–H reduces both the material available for leaching and the calcium hydroxide that participates in sulfate and acid attack. A caution attaches to the calcareous and high-carbon ashes, however. Ashes with a high loss on ignition (coffee husk at 28%, volcanic ash at 14%) carry unburnt carbon that can increase porosity and admixture demand, and sewage sludge and some industrial ashes carry heavy metals whose leaching must be verified. Durability gains are thus contingent on the ash being reactive, finely divided and low in carbon; where these conditions are not met, high replacement can worsen rather than improve durability.

➤ *Microstructural and Mineralogical Evidence*

The macroscopic trends are underpinned by microstructural observations reported in the more instrumented studies. Scanning electron microscopy of ash-blended pastes shows a denser matrix with reduced portlandite and additional C–S–H at the optimum replacement, and increasing porosity and unreacted ash particles beyond it. Kareem and colleagues used electron microscopy to link the porosity of high-cashew-leaf-ash mixes to the shortage of calcium hydroxide available to react with the added silica, explaining the strength drop above 5% [18]. X-ray diffraction and thermogravimetry were used by Rodier and colleagues and by Memon and colleagues to quantify the amorphous silica content and the pozzolanic consumption of portlandite, and the Chapelle test provided a direct chemical measure of reactivity, 345–352 mg CaO/g for bamboo stem ash and 1294 mg CaO/g for processed bagasse ash against the 330 mg/g reactivity threshold [8], [6]. These techniques collectively confirm that the strength optimum coincides with the point at which the reactive silica of the ash is stoichiometrically balanced against the portlandite supply.

➤ *Environmental and Economic Assessment*

The environmental case for ash replacement rests on two pillars. The first is the avoided clinker: because roughly 0.8–0.9 tonnes of carbon dioxide accompany each tonne of cement, every tonne of clinker displaced by ash yields a nearly proportional reduction in the embodied carbon of the binder [36]. Ibeto and colleagues quantified this directly through a carbon-emission simulation, confirming a lower pollution potential for the coal-ash-blended concretes [27], and several agricultural-ash studies frame a 10% replacement as reducing binder-related emissions by a comparable fraction [10]. The second pillar is waste diversion: rice husk, bagasse, coffee husk, palm residues, sawdust, shells and municipal sludge are otherwise landfilled or openly burned, and their conversion into a cement substitute removes both the disposal burden and, in the case of open burning, a source of particulate air pollution [19], [30].

The economic case is strongest where the ash is a local waste with a low or negative acquisition cost. Bhushan and colleagues measured a 3% reduction in concrete cost from rice husk ash replacement [3], and the recurring motivation across the African and South Asian studies is the high and rising price of cement in those markets. The economic balance must, however, account for the processing that reactivity often requires: controlled calcination to fix the silica in its amorphous form, and grinding to a high specific surface area. These steps carry their own energy and cost, and for ashes that demand intensive processing the net benefit is smaller than the raw-material saving suggests. Date palm ash and sewage sludge ash carry the additional requirement of leaching verification, since their beneficial use is predicated on the safe immobilisation of trace metals within the matrix [19], [30].

VIII. CHALLENGES AND LIMITATIONS

Several obstacles stand between the promising laboratory results surveyed here and the routine industrial use of alternative ashes.

The first is feedstock variability. The oxide chemistry of an agricultural ash depends on the crop variety, the soil, the fertiliser regime, the combustion temperature and atmosphere, and the residence time. The same nominal ash can therefore range from a reactive pozzolan to an inert diluent, as the contrast between well-burnt and open-burnt rice husk ash shows [2], [4]. Without control of the burning process, reproducibility cannot be guaranteed.

The second is the energy and cost of processing. Achieving amorphous silica requires calcination within a fairly narrow temperature window (commonly 500–700 °C for husks, higher for shells), and achieving reactivity requires grinding to a high fineness. Both steps consume energy that offsets part of the environmental benefit and adds cost.

The third is the loss on ignition and unburnt carbon. Ashes such as coffee husk (LOI 28%) and coconut shell (LOI 12%) carry carbon that increases water and admixture demand and can impair air-entrainment and durability. The fourth is the presence of deleterious constituents: heavy metals in sewage sludge ash, arsenic in date palm ash, and high alkali (K₂O) in several leaf and husk ashes, which raises a potential alkali–silica-reaction concern that few of the studies examined.

The fifth, and perhaps the most consequential for adoption, is the absence of harmonised standards. ASTM C618 and its equivalents were written for coal fly ash and natural pozzolans; there is no widely accepted specification governing rice husk, bagasse, shell or sludge ashes, and in its absence engineers and codes are reluctant to permit their structural use. Finally, most of the source studies are laboratory-scale, short-term (frequently 28-day) investigations of a single ash source; field-scale trials, long-term durability data, and studies of ash combinations remain scarce. A further caution concerns the evidence base itself: a proportion of the primary studies appear in journals with limited editorial oversight, and the absence of reported measurement uncertainty in most of them means that small

differences between an ash mix and its control should be treated with corresponding reserve.

IX. FUTURE RESEARCH DIRECTIONS

The literature points to several priorities. Controlled and, ideally, energy-recovering combustion of agricultural residues should be standardised so that reactive amorphous ash is produced reproducibly, coupling waste-to-energy generation with a consistent SCM output. Chemical and mechanical activation, exemplified by the lime activation that allowed ferrochrome ash to reach a 47% replacement [29] and by the controlled grinding that sharply raised the reactivity of bagasse ash [6], deserves systematic study across the agricultural ashes as a route to higher usable replacement. Ternary and quaternary blends that pair a siliceous ash (rice husk, bagasse, wheat straw) with a calcareous one (wood, shell, bone) are a promising and largely unexplored avenue, since the lime of the calcareous ash could feed the pozzolanic reaction of the siliceous one. Long-term durability, including chloride ingress, sulfate resistance, carbonation and, given the high alkali content of several ashes, alkali-silica reaction, must be characterised beyond the 28-day horizon that dominates the current data. The trace-metal leaching of sludge, bone and shell ashes needs standardised assessment to satisfy environmental regulators. Above all, the development of performance-based standards for non-coal ashes is the essential enabling step; without it the structural use of these materials will remain confined to research. Life-cycle assessment and field-scale demonstration should accompany that standards work so that the environmental and economic claims made at laboratory scale are verified in practice.

X. CONCLUSIONS

This review synthesised thirty-five studies covering more than twenty ash types used as partial replacements for Portland cement, and the following conclusions emerge.

First, ashes divide cleanly by chemistry into reactive pozzolans and calcareous fillers. The siliceous agricultural ashes (rice husk, sugarcane bagasse, wheat straw, palm oil fuel, sawdust, bamboo) and the coal-derived ashes approach or exceed the 70% combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ benchmark that ASTM C618 applies to Class N natural pozzolans, and behave as genuine pozzolans, forming secondary C-S-H that maintains or improves strength. The calcareous ashes (wood, walnut shell, seashell, cattle bone, biomass bottom) fall well below the benchmark and act as fillers and lime sources rather than pozzolans.

Second, every ash exhibits an optimum replacement level beyond which strength declines, because the added reactive silica eventually outstrips the calcium hydroxide available from the diminishing clinker. Across the literature this optimum clusters between 5% and 15% by mass for the agricultural and marine ashes, extends to 20% for volcanic ash and Class F fly ash, and reaches 40–47% for ferrochrome ash activated with lime. For the majority of alternative ashes, a replacement of about 10% is a safe and effective general recommendation.

Third, the benefits extend beyond strength. Reactive ashes at their optimum refine the pore structure, lower water absorption and permeability, and improve durability, while the replacement of clinker cuts embodied carbon nearly in proportion and diverts large waste streams from disposal. The strongest performers combine a genuinely siliceous, amorphous, finely ground ash with modest replacement and adequate curing.

Fourth, the principal barriers to adoption are feedstock variability, the energy cost of controlled calcination and grinding, deleterious constituents such as unburnt carbon and heavy metals, and, decisively, the absence of standards for non-coal ashes. Progress toward routine use depends less on discovering new ashes than on standardising the production of the ones already known to work, activating them to raise usable replacement, characterising their long-term durability, and writing the performance-based specifications that would let engineers use them with confidence. On the evidence assembled here, ash as a partial cement replacement is not a marginal expedient but a mature and underused strategy for lowering the carbon and cost of concrete, awaiting mainly the standards and processing discipline needed to deploy it at scale.

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