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Making low-clinker cements work: Constraints, chemical activation, and region-specific pathways

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Abstract

Decarbonising cement requires lowering the clinker factor, yet binders in which clinker falls below about half of the binder mass often suffer kinetic and thermodynamic constraints that delay early strength and leave durability performance uncertain. Chemical activation, through calcium-based additives, low-dosage salts, hybrid alkaline systems, nucleation seeding, or alkanolamines, is the most direct means of recovering early performance, although each route trades early against later-age behaviour and carries an embodied carbon cost of its own. Because cement production and resource availability vary strongly by region, locally available precursors such as low-grade calcined clays, industrial by-products, and natural pozzolans must anchor regional pathways, even as centralised, traded supply chains coexist with regional ones. This letter argues that low-clinker binders underperform less because a single technical solution is missing than because activation chemistry, the locally available precursor, and the target application are treated in isolation, and that this technical difficulty is compounded by the scarcity of performance-based specifications in many regions and by the hesitancy of practitioners even where such specifications already exist. Since a large share of cement serves unreinforced and lightly loaded applications, low-clinker binders can be deployed there with confidence today, while durability data and performance-based specifications mature for reinforced and structural application.

Keywords: Cement decarbonisation; Low-clinker cement; Chemical activation; Supplementary cementitious materials; Performance-based standards

1 Introduction

Concrete is the most used manufactured material on Earth and the foundation of modern construction, yet its binder, Portland cement (PC), accounts for 7 to 8% of anthropogenic CO_2 emissions, of which more than half is process CO_2 released when limestone is decarbonated at temperatures approaching 1450 ℃ [1]. Deep decarbonisation therefore depends on reducing the clinker factor, the mass ratio of clinker to total binder. With global floor area set to grow with population toward 2050, a business-as-usual trajectory is untenable [1]. The International Energy Agency (IEA) placed the global clinker-to-cement ratio near 0.71 in 2022 [2], rising at an average annual rate of 1.1% since 2015, and the overall assessment shows that decarbonisation of the cement industry remains off track [3]. To align with the Paris Agreement, the Global Cement and Concrete Association (GCCA) roadmap calls for the average clinker-to binder ratio to fall from a 2020 baseline of 0.63 to 0.58 by 2030 and to 0.52 by 2050 [4], whereas the IEA projects a ratio of 0.57 by 2050 [2].

Reducing the clinker factor is only one of several routes to low-carbon cement. Alternative process chemistries, including alkali-activated materials, calcium-silicate clinkers, and electrochemically synthesised cements, also pursue low-carbon binders but fall outside the scope of this letter. The focus here is on binders in which clinker is deliberately reduced to 0.50 or below, referred to as low-clinker cements. Below this threshold, conventional blended cement behaviour becomes kinetically and thermodynamically constrained, and the barriers to reliable performance are not only chemical and mechanical but also regulatory. The most familiar constraint in these systems is the early-age performance gap. Conventional blended cements rely on a pozzolanic reaction that consumes the portlandite released by clinker hydration. As the clinker factor falls well below 0.50, the portlandite reserve can become limiting, so that setting and early strength development slow [5, 6]. Some low-clinker

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systems such as limestone calcined clay cement (LC3) recover much of the lost performance due to limestone-clay synergies and secondary aluminate reactions, and well-designed LC3 systems can reach a clinker factor near 0.50 without chemical activation [7]. High-slag systems can go further still, attaining clinker factors below 0.50 without activation, because the intrinsic calcium content and latent hydraulicity of slag sustain hydration where purely pozzolanic materials cannot [8]. This exception is bound to the particular chemistry and stoichiometry of slag and does not generalise: most present and prospective supplementary cementitious materials (SCMs), including calcined clays and the majority of industrial residues, are aluminosilicate materials with little intrinsic calcium, and availability of slag itself is limited in several regions. Because this letter is concerned with the forward pathway, in which fly ash and slag supplies are expected to decline while aluminosilicate precursors dominate, the central difficulty remains: below about 0.50 clinker, and for less reactive or lower-grade precursors, slow setting and early strength loss render high substitution mixes impractical.

This letter addresses the practical deployment of low-clinker cements with clinker factors at or below 0.50. It examines the chemical activation pathways that can recover early strength, the carbon cost that must be justified by a net-benefit condition (explained in section 3), the durability uncertainties that remain unresolved, the regional resource matching that determines which activators work where, and the regulatory and professional barriers that still limit uptake despite recent progress in performance-based and dedicated low-clinker standards. The aim is to distinguish settled chemistry from open questions and to show how region-specific supply and application-tiered deployment can accelerate near-term emissions reductions. Fig. 1 summarises this framework.

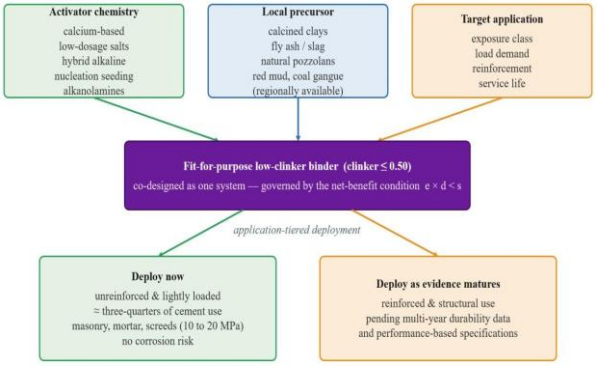


Figure 1. The matching framework: activator chemistry, the local precursor, and the target application co-designed as one system under the net-benefit condition e × d < s, then deployed in two tiers, unreinforced and lightly loaded use now and reinforced use as evidence matures.

2 Chemical pathways for clinker reduction below 50%

Performance recovery at very low clinker contents can be pursued in two ways: through ex-situ pre-treatment of the precursors, for example thermal activation, high-energy mechanical amorphisation, or acid treatment, or through in-situ chemical activation during hydration. This letter concentrates on the latter, because soluble admixtures acting in situ provide the most direct and flexible route to performance recovery and adapt readily to diverse material streams. They manipulate pore-solution chemistry and reaction kinetics at ambient temperature, and range from synergistic calcium-based accelerators [9] and low dosage alkali salts [10, 11] to high dosage hybrid alkaline cements [12], C-S-H seeding [13], acid activation [14], and emerging alkanolamines [15]. In binders with a clinker factor at or below 0.50, chemical activation is the principal means of offsetting the low portlandite reserve and reduced pore-solution pH, supporting early strength while, at appropriate dosages, preserving long-term performance [16].

2.1 Calcium-based activators

Synergistic calcium-based activators are attractive because they simultaneously supply reactive calcium and catalyse hydration. In a binder containing 10% clinker, combining $Ca(OH)_2$ with calcium formate raised the one-day compressive strength from 1.7 to 15.7 MPa [9]: $Ca(OH)_2$ provides the necessary alkalinity and supplies Ca^{2+} that catalyse the dissolution of fly ash (FA) and slag aluminosilicates with formate ions ($HCOO^-$) accelerating clinker dissolution and transforming into microstructural calcite under high pH. Where the formate is produced from captured CO_2, this route can further lower the embodied carbon of ultra-low-clinker binders [17].

In limestone calcined clay cements (LC3), clinker factors below 50 % can achieve strengths equivalent to traditional Portland–pozzolana cement while reducing clinker content to 25–35 % [18]. However, the portlandite from clinker hydration is consumed within days, and adding commercial $Ca(OH)_2$ at the high dosages then required can raise the carbon footprint enough to undercut the low-carbon objective. The case of LC3 binders produced from low-grade Indonesian clays (26 to 67% kaolinite) demonstrates the risk of excessive calcium addition: strength declined when clinker content was reduced from 50% to 30%, and the introduction of supplementary $Ca(OH)_2$ further reduced rather than enhanced performance[19], because the $Ca(OH)_2$ addition reached 16 to 50% of the calcined-clay mass, far above the pozzolanic demand. This led to elevated pH unsuitable for the pozzolanic reaction, which promoted strätlingite and ettringite formation and led to a porous microstructure. Waste-derived calcium avoids this penalty. Using $Ca(OH)_2$ recovered from carbide slag, an acetylene by-product, LC^3 blends with a clinker factor as low as 0.30 reached 40 MPa with a microstructure comparable to LC3-50 and markedly better than PC [6], and optimised carbide-slag dosages in 50%-clinker LC3 maintained or enhanced strength [20]. In high-volume FA systems with about 20% clinker, a co-activator of 10% $Ca(OH)_2$ and 4% Na_2SO_4 shortened the induction period and promoted early ettringite and C-S-H, densifying the matrix [21].

2.2 Low-dosage alkali and salt activators

Low-dosage alkali and salt activators modulate hydration kinetics in high-SCM systems. In an 80% FA, 20% PC binder, NaOH markedly increased the reaction of both FA and clinker and improved early strength, although the long-term strength converged with the unactivated control [10]. Alkalinity also governs product packing: at 1.0 M NaOH the C-A-S-H gel forms loose, sheet-like clusters, whereas 0.2 M NaOH yields a denser matrix [10]. Alkali sulfates such as Na_2SO4 and K_2SO_4 are more effective than alkali hydroxides (NaOH, KOH) for improving compressive strength, due to ettringite formation. The optimal Na_2O equivalent was identified as 0.5%. While sulfates accelerated early hydration, they retarded later-age hydration; however, calcium sulfate ($CaSO_4$) showed less deleterious effects at later ages compared to alkali sulfates. [22]. Collectively, these findings show a fundamental trade-off: low-dosage alkalis effectively resolve early-age strength deficiencies, but without careful optimisation they can impair long-term hydration degree and durability [22].

2.3 Hybrid alkaline cements

Hybrid alkaline cements (HACs) combine a higher activator dosage (above 4 to 5% by mass) with a small clinker fraction (below 30%) and a large SCM content (at least 70%). The activator, most often Na_2SO_4 for its practicality over hazardous NaOH or silicate, drives SCM dissolution [23]. Solid Na_2SO_4 at 5 to 6% with 30% clinker gives useful early and 28-day strengths. Mechanistically, the added sulfate is taken up by reaction with portlandite-derived Ca^{2+} and aluminate phases to form gypsum and, ultimately, ettringite (AFt); the released sodium remains in the pore solution, where charge balance requires a corresponding rise in OH^-, and the resulting increase in alkalinity accelerates SCM dissolution [22, 24]. In clay-based HACs, 5% Na_2SO_4 in a 60% dehydroxylated bentonite and 40% clinker blend raised alkalinity, enhanced bentonite dissolution, and formed (N,C)-A-S-H and C-A-S-H gels with AFm phases, exceeding the 28-day strength of pure PC paste [25]. In metakaolin-limestone-clinker systems, limestone up to 25% refines pores through carboaluminate formation and offsets sulfate-induced later-age porosity. Comparing Na_2SO_4, Na_2SiO_3, and Na_2CO_3 in a 25% clinker, 50% calcined clay, 25% limestone binder, Na_2SO_4 at 1.5% Na_2O equivalent was optimal, raising two-day strength by about 160% to roughly 18.8 MPa with only a minor 28-day penalty, through improved solid-phase connectivity and stable ettringite and without significant change in total porosity [11].

For slag-FA HACs containing a small clinker addition (4.8–14.4%), curing at 10°C gave up to 27% higher 91-day strength than at 21.5°C, linked to strätlingite and C-N-A-S-H formation and confirming cold-weather viability. This benefit was not observed in the alkali-activated slag-fly ash blend without clinker, which showed higher strength at 21.5°C [26]. One-part, just-add-water HACs (25 to 30% PC, 70 to 75% SCMs, 1.5 to 8% dry salt) remove the logistics of liquid activators [27, 28], but they demand balance: too little clinker leaves the pore solution below the pH needed for SCM dissolution, while excess salt can saturate the C-S-H gel and cause late-age expansion or ettringite shells that stifle further reaction. Continued refinement of solid-state, near-neutral activators positions HACs as a credible, scalable pathway for decarbonising cementitious construction once performance-based standards and industrial protocols are fully established.

2.4 Nucleation seeding and nanoscale additives

C-S-H seeding introduces pre-synthesised nanoparticles that supply abundant low-energy sites for C-S-H precipitation. By multiplying the number of nucleation points, the seeds lower the apparent activation energy of hydration, couple C-S-H growth to alite dissolution, and shift precipitation from the surfaces of dissolving grains into the capillary pore space, producing a denser and more homogeneous microstructure [13]. The action is one of accelerated nucleation and growth rather than a change in pore-solution chemistry: the C-S-H seeds principally speed clinker hydration including the acceleration in pH [8] and supply additional hydrate volume rather than activate the supplementary cementitious materials. Consistent with this, the benefit is larger in blended and low-clinker binders than in plain Portland cement. Li et al. [29] reported that 1.5 to 2.0 wt% C-S-H seeding in an LC^3-slag cement reached strength comparable to neat Portland cement at only 20% clinker, and a tailored seeding admixture improved both the one-day and 28-day strength of LC^3-50 mortars [30].

Aluminium-bearing seeds designed for calcined-clay systems are a partial exception. C-A-S-H nano-seeds with an Al/Si ratio near 0.10 outperform conventional C-S-H seeds in early strength and setting, and ^{27}Al NMR confirms that they enhance the reaction of metakaolin and favour CA-S-H over AFt and AFm phases [31], a templating effect on the supplementary phase rather than a pH-driven one. Nano-silica behaves differently again: being pozzolanically reactive, it both nucleates and consumes portlandite, refining the pore structure of ultra-low-clinker blends (clinker at or below 5%) [32], although its early acceleration in LC3-50 can be offset by later-age retardation [24]. Graphene oxide at 0.1% raised one-day strength by 26% in a 49% PC, 35% slag, 16% limestone ternary system but accelerated surface carbonation [33].

The capacity of these nano-seeds to manipulate the nucleation landscape and gel morphology makes them a valuable complement to chemical activation. Their scalability, however, remains limited by high cost, agglomeration and dispersion difficulties, uncertain long-term performance, and incompatibility with conventional admixtures, despite two decades of study in cementitious systems [34]. Their behaviour in genuinely low-clinker blends also requires further validation.

2.5 Alkanolamine activation

Although few studies sit strictly below 0.50 clinker, the evidence for alkanolamines such as triethanolamine (TEA), triisopropanolamine (TIPA), and diethanolisopropanolamine

(DEIPA) as activators, beyond their established role as grinding aids, is compelling. In LC3 [35] and supersulfated slag cements [36], alkanolamines chemically alter the morphology and chemical composition of the aluminate hydrates and C-A-S-H gels. TIPA, in particular, heavily favors the hydration of the ferrite phase (C_4AF) in residual clinker and drastically accelerates the silicate reaction of metakaolin [35] and the breakdown of slag [36]. Chelation of alkanolamines with Al^{3+} ions accelerates the decomposition of the SCM glassy matrices and ettringite formation in SSC [36]. Blending these amines (e.g., 75% TIPA and 25% TEA) creates a synergistic effect where TEA strengthens early Ca^{2+} binding while TIPA's steric profile tunes particle packing and coverage, acting as a low-molecular-weight analogue to PCEs to organize the interfacial transition zone [37]. The essential practical point is that alkanolamines are strongly dose-sensitive: the optimum window is narrow, and overdosing can retard set or depress later strength, so they must be dosed to each binder rather than applied by rule of thumb.

2.6 Alternative routes

Chemically activated red mud offers waste valorisation potential, enabling higher clinker replacement (40–50 %) when combined with FA [38], metakaolin, or carbonation pre-treatment [39]. However, its variable mineralogy, high inherent alkalinity, and heavy-metal leaching risks impose rigorous pre-treatment and regulatory burdens, limiting viability to regions with consistent bauxite residue supplies and strict environmental controls (> 4 billion tons stockpiles in China) [38]. Calcium chloride, while economical and effective for early strength, is severely restricted in structural concrete by corrosion risk to steel reinforcement [40, 41]. However, 3D concrete printing (3DCP) offers an ideal niche for the use of chloride admixtures (NaCl and $CaCl_2$), which are prohibited in reinforced concrete [40], as 3DCP routinely uses no steel reinforcement with high clinker content. Superplasticizers and low w/b ratios (0.14–0.25) are not activators per se but are non-negotiable enablers for high-performance ultra-low-clinker cements, with particle packing optimization preserving mechanical and microstructural performance [40, 42]. Chloride-free calcium aluminate and calcium nitrite-based accelerators deliver significant early- and later-age strength improvements in low-clinker systems [43] but extensive long-term durability data are lacking and need further investigation. Novel SCMs such as partially calcined waste dolomite, when paired with calcined clay (LC^3-20), generate a synergistic hydration effect that overcomes natural inertness and increases strength by over 90% at 7 and 28 days. This approach creates a core-shell structure that accelerates the formation of beneficial hydration products, resulting in high-strength binders with a 43% reduction in CO_2 emissions [44].

3 A net-benefit condition for activator footprints

Whether activation genuinely contributes to climate mitigation can be assessed through a simple inequality. Let $\boldsymbol{e}$ denote the embodied CO_2 of an activator per unit mass, $\boldsymbol{d}$ its dosage as a fraction of binder mass, and $\boldsymbol{s}$ the CO_2 avoided per unit binder through the clinker that the strategy allows to be removed. Activation yields a net benefit only when $\boldsymbol{e \times d < s}$. Because most activators act at low dosage, the product $\boldsymbol{e \times d}$ is small, which is why targeted activation preserves the savings from clinker reduction, whereas high-dosage alkaline systems can violate the inequality.

The carbon intensities of common activators are now reasonably well established. Typical production emissions are NaOH ~0.63–1.92 $kgCO_2/kg$, Na_2SiO_3 ~0.99 $kgCO_2/kg$ [45]; triethanolamine ~3.03 and TIPA ~0.42 $kgCO_2/kg$ [46]; C–S–H seed admixtures ~0.72 $kgCO_2/kg$ [46]; calcined clay ~0.25–0.39 $kgCO_2/kg$ [46].

Table 1. Comparison of chemical activation strategies for low-clinker binders against the net-benefit condition

Activation strategy	Typical dosage	Embodied CO_2 (kg CO_2/kg)	Principal effect	Net-benefit (relative)
$Ca(OH)_2$ + calcium formate	5 to 15% CH + formate	formate 0.4 to 3.0 (source-dependent)	early strength via Ca^{2+} and calcite	favourable if CH not overdosed
Waste-derived $Ca(OH)_2$ (carbide slag)	replaces industrial CH	~0 (waste-derived)	reactive Ca; densifies matrix	highly favourable
Low-dosage Na_2SO_4	1.5 to 6%	0.2 to 0.4	early ettringite; raises pore pH	favourable
High-dosage NaOH / Na_2SiO_3 (HAC)	4 to 8%+	NaOH 0.63 to 1.92; Na_2SiO_3 ~0.99	strong SCM dissolution	marginal; may violate condition
C-S-H / C-A-S-H nano-seeding	0.5 to 3%	seed ~0.72	nucleation and acceleration	favourable (small mass)
Alkanolamines (TEA/TIPA/DEIPA)	0.02 to 0.1%	TEA ~3.03; TIPA ~0.42	accelerate ferrite/SCM reaction	favourable but dose-sensitive

High-SCM binders with 30 to 50% clinker already reduce CO_2 by 30 to 50% without exotic additives [6]. Small additions of C-S-H seeds [47], alkanolamines [36], Na_2SO_4 [48], or calcium formate [9] restore early strength at a minor carbon cost, typically well within the inequality because the footprint is amortised over an addition of only a few percent by mass.

Table 1 applies this condition to the principal activation routes and indicates the strength of the supporting evidence. The practical implication is that activation must be evaluated on a case-by-case basis: high dosages of synthetic sodium silicates or hydroxides can cancel a large share of the clinker saving and increase the cost per cubic metre, and are justified only where no lower-footprint route delivers the required performance.

4 Durability of low-clinker binders

Assessing the durability of low-clinker cements requires a clear separation between well-established findings and areas where the evidence remains incomplete or contested. Against chloride ingress, low-clinker systems such as LC3 and supersulfated cements clearly outperform PC, owing to a tortuous, refined pore network [49, 50], and their resistance to alkali-silica reaction is likewise strong [51]. Other aspects are less settled. Carbonation is a recognised vulnerability: LC^3 [50] and similar blends (with clinker content below 50%) carbonate more rapidly than PC because their reduced portlandite reserve lowers the alkaline buffer capacity; once portlandite is locally consumed, the C-A-S-H gel decalcifies and the carbonation front advances [52, 53] More concerning, recent evidence indicates that carbonation-induced depassivation of steel can begin before the carbonation front physically reaches the bar [54], shifting the critical question from carbonation depth to corrosion initiation. HACs show promising resistance to sulfate attack, alkali-silica reaction, and elevated temperature, yet remain susceptible to carbonation [55].

Overall, the durability database is not yet sufficient to support unconditional confidence across all exposure conditions. Most published studies are confined to 28 to 90 days, whereas the critical uncertainties demand far longer observation. These include alkali-silica reaction under sustained moisture, carbonation beyond accelerated laboratory tests, strength retention after realistic curing, and reinforcement corrosion in activated systems. Until multi-year datasets addressing these phenomena are available, structural adoption will proceed cautiously, and performance-based verification for each combination of binder chemistry and exposure should be treated as a prerequisite rather than an option.

5 Regional precursors and tailored strategies

The geography of cement has shifted decisively. OECD countries held 64% of output in 1970 but only 12% by 2020 [56]. Demand has stabilised in most developed economies, while South Asia, Southeast Asia, Sub-Saharan Africa, and Latin America enter materials-intensive urbanisation, with their combined share projected near 54% by 2035 (Fig. 2) [1]. Fig. 2 makes the point starkly: China peaked around 2020 and declines thereafter, while India, other Asia, and Africa together roughly quadruple to 2050.

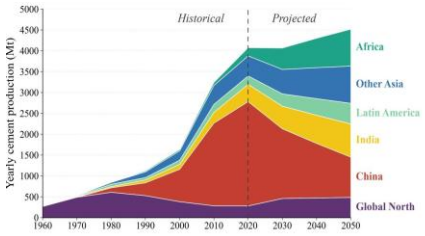


Figure 2. Past and future cement production by region, 1960 to 2050 (Mt), redrawn by the author from the regional production data of Boanada-Fuchs, Heierli and Scrivener [1]. China peaks around 2020 and declines thereafter, while India, other Asia, Latin America and Africa grow strongly to 2050.

This shifting geography makes a substantially regional approach to decarbonisation unavoidable, since transporting high-volume, low-value materials over long distances is rarely economic. A centralised, traded model, in which clinker, slag, and calcined clay are produced at scale and blended near end-markets, already exists and will continue alongside regional supply; indeed, intercontinental trade and cross-border consolidation among major producers are expanding [57, 58]. That model has real limits for importing regions, however. First, the presence of a resource, whether clay or an industrial by-product, does not guarantee the processing technology, kiln-retrofit capability, and technical expertise needed to convert it into a reliable binder. Second, logistical constraints extend well beyond shipping to underdeveloped ports and fragmented rail, road, and storage networks that impede material movement even within national borders. Third, a heavy reliance on imported constituents can slow the growth of local production capacity and expose importing regions to the carbon-leakage and value-capture asymmetries that a just transition is meant to avoid [59]. A regionally anchored strategy built on local precursors is therefore preferable on both economic and developmental grounds, without excluding trade where it is genuinely efficient. The distribution of clay and limestone (Fig. 3a) and of industrial by-products (Fig. 3b), summarised for the main waste streams in Fig. 4, indicates both the opportunity and the logistical challenge.

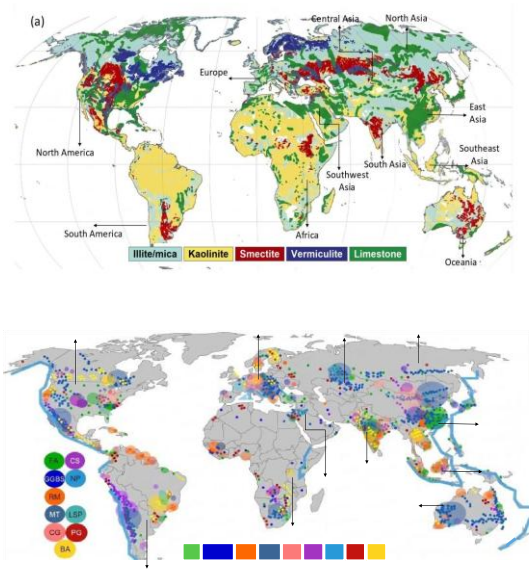


Figure 3. (a) Global distribution of dominant sub-soil clay minerals (illite/mica, kaolinite, smectite, vermiculite) and limestone, indicating regions favourable for LC3 scalability (merged by image registration from the global clay-mineral map of Ito and Wagai [60] and the carbonate-rock map reproduced by Xu et al. [61]). (b) Availability of alternative materials across major world regions (FA = fly ash, GGBS = ground granulated blast-furnace slag, RM = red mud, MT = mine tailings, CG = coal gangue, CS = copper slag, VA = volcanic ash, PG = phosphogypsum, BA = biomass ash). The spatial distribution of industrial by-products was compiled from publicly available online maps and databases of industrial facilities relevant to each by-product (e.g., the Global Energy Monitor coal-plant and steel-plant trackers) and manually geolocated to reflect regional availability.

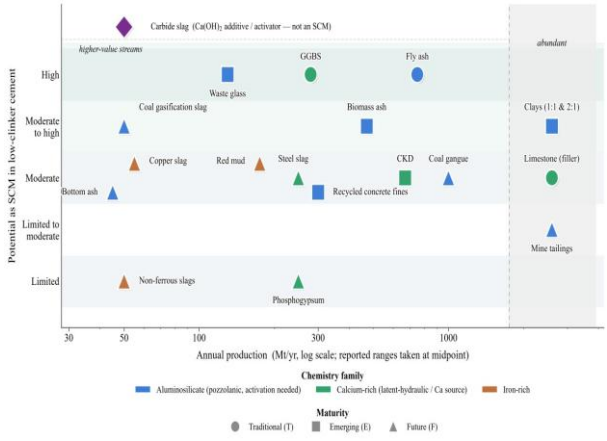


Figure 4. Availability versus SCM potential of candidate waste streams. Each stream is positioned by annual production (log scale) and rated SCM potential; marker colour denotes chemistry family and shape denotes maturity (T= traditional, E= emerging, F= future). The shaded upper rows mark the higher-value streams; the right-hand band holds streams reported as abundant but without a quantified production. The figure is built from the data provided in [62].

By-product geography tracks industrialisation. China dominates almost every major traditional, emerging, and future stream, from FA and red mud to steel slag, cement kiln dust, and coal gangue, and vast stockpiles of red mud, phosphogypsum, and coal gangue persist, while mine tailings, the largest stream by volume, remain grossly underused; thermally activated coal gangue can already substitute for metakaolin in LC^3. India follows and will intensify. It holds extensive kaolinitic clay, and roughly 70% of its market already uses blended cements underpinned by abundant FA, of which about 330 Mt was utilised in 2024 to 2025, with the cement sector a major consumer [63, 64]. Industrial-scale LC3 has been validated at multiple Indian plants using lower-grade clay and limestone without performance loss [65], and the IS 18189:2023 standard has enabled commercial production [66, 67]. The near-term priority could be to embed LC^3 in public procurement while mobilising the wider pool of by-products.

Sub-Saharan Africa holds extensive kaolinitic and 2:1 clays such as illite and smectite [68–70]. For 2:1 clays, mechanochemical activation offers a distinct advantage over thermal activation, since it can achieve comparable or even superior reactivity for a similar energy input, with the important qualification that it substitutes costly electricity for the fuel used in thermal activation [71] . Central and southern Africa also offer natural pozzolans such as volcanic scoria and pumice that need only grinding, together with phosphogypsum as a calcium-rich additive [72, 73]. Suitable clays exist continent-wide, but national standards often fail to recognise them, which the LC^3 TRC Africa initiative is working to amend [74, 75].

Latin America and the Caribbean offer one of the strongest calcined-clay bases outside Asia: Brazil has produced calcined clay since the 1970s at about 2 Mt per year, and Colombia now runs some 500,000 t per year of capacity at roughly 550 kcal/kg, about 30% below a dry clinker line, with blended cements also produced in Argentina and piloted in Cuba and Guatemala [76]. Volcanic natural pozzolans are abundant along the Andes, the trans-Mexican volcanic belt, and Central America, but their use is bounded by distance from cities, favouring Chile, Ecuador, Mexico, Nicaragua, and Peru, while Brazil lacks them geologically. With coal at only about 5% of regional electricity in 2019 and declining, fly ash and slag are receding, so recycled ceramics, copper and ferronickel slags, and agro-industrial ashes such as rice husk ash supply real but locally limited volumes [76].

In Europe and North America, declining FA and slag supply is pushing the field toward recycled concrete fines, waste glass, municipal-solid-waste incineration bottom ash, reclaimed fly ash, and mine tailings, all of which need beneficiation and activation [77]. Momentum behind clay-based and engineered SCMs is building, from the first-of-its-kind thyssenkrupp mechanochemical clay unit under construction in Germany, an early commercial demonstration [78], to North American ventures producing engineered SCMs such as Fortera and Terra CO_2 [79, 80].

The practical priority, in the author's view, is to pair each region's most abundant precursor with performance-based specification and targeted public procurement, so that

demand is created for binders the region can genuinely produce.

6 A perspective on clinker-reduction trajectories

The regional resource and technology trends set out above suggest a qualitative trajectory for the clinker factor, offered here as the author's qualitative synthesis rather than a formal macroeconomic forecast. Grey clinker is expected to decline steadily over the coming decades. Traditional industrial SCMs, chiefly fly ash and blast-furnace slag, fall in relative share as rapidly industrialising economies consume their own by-products and coal-fired power is phased down. Natural SCMs and mineral fillers grow to become the dominant substitute, innovative SCMs and alternative binders reach meaningful deployment, and green clinker from carbon capture, utilisation and storage (CCUS) emerges but stays concentrated in economies that possess the necessary capital and infrastructure. This direction is consistent with the GCCA target of a clinker factor approaching 0.50 by mid-century. The GCCA Net Zero Accelerator supports national industries in building localised roadmaps (Fig. 5) aligned with regional materials availability and market conditions [81], however only a handful countries, producing approximately 12% to 15% of total world cement production have joined this program.

Both the GCCA global roadmap and the national roadmaps prepared under its Net Zero Accelerator assign carbon capture the single largest share of projected reductions, about one third of the total globally and in several national pathways, closer to one half [81]. However, actual deployment remains nascent. By 2025 only the world's first industrial-scale cement carbon-capture plant, the Brevik facility of Heidelberg Materials in Norway, had been commissioned, and current projections place less than 2% of global cement emissions under capture by 2035 [82].

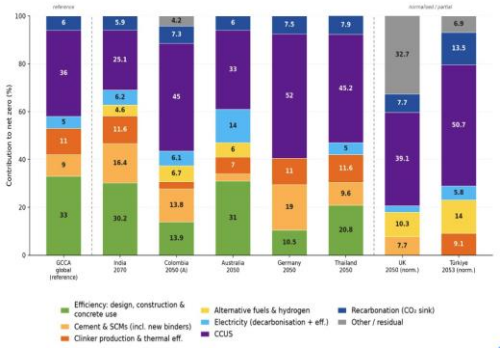


Figure 5. Contribution of the principal decarbonisation levers to net zero in cement and concrete roadmaps, expressed as a share of each roadmap's total projected CO_2 reduction. The GCCA global roadmap is shown at the left as a reference. The six bars to the left of the second divider (the GCCA global reference together with the India, Colombia, Australia, Germany and Thailand roadmaps) report complete per-lever splits; the UK and Türkiye bars to the right are shown on a normalised or partial basis. Carbon capture, utilisation and storage (CCUS) is the single largest lever in seven of the eight roadmaps, the exception being India, where cement-use efficiency (30.2%) slightly exceeds CCUS (25.1%).

Because the technology is capital-intensive and infrastructure-dependent, it will realistically remain more concentrated in the Global North in near future, whose share of clinker production is falling or remains constant, while adding a cost that importing economies are least able to absorb. Tellingly, in the roadmaps written for fast-growing developing economies, efficiency in cement use and supplementary materials already rival or exceed carbon capture as the leading levers, which is precisely where the near-term opportunity lies. CCUS is therefore best understood as a genuine but geographically bounded lever: valuable for decarbonising a shrinking Northern clinker base, yet unlikely to scale quickly across the Global South, where the credible near-term levers are abundant local wastes, natural SCMs, and disciplined chemical activation. In the author’s opinion, the weight placed on CCUS therefore warrants caution, particularly in the emerging economies of the Global South.

7 From prescriptive codes to performance-based deployment

Regulation is both the binding constraint and the largest near-term opportunity, and it operates at two levels that are easily conflated. Design codes govern the structure and the concrete as placed, for example EN 1992, ACI 318, and IS 456, together with the concrete standards EN 206 and ACI 301, whereas material specifications govern the binder itself, that is, the cement and its supplementary materials. Both have historically been prescriptive and deemed-to-satisfy: the minimum cement contents and maximum water-to-binder ratios that most penalise low-clinker binders sit in the concrete design codes, while cement specifications have long fixed composition by recipe. Many of these rules were set before modern admixtures existed, and both levels discourage mix optimisation and penalise low-clinker binders even when their early strength and durability are adequate. The distinction matters because progress on one level does not guarantee the other: many countries have moved their building codes toward performance, yet their cement specifications, and the concrete codes that admit a binder into load-bearing use, remain prescriptive, so the binder is still judged by recipe rather than by how it performs.

Two regulatory routes are now opening the door to low-clinker binders, and they are worth distinguishing (Table 2). The first is genuinely performance-based specification, which qualifies a binder by what it does rather than what it contains. The clearest example is ASTM C1157 in the United States, which prescribes no composition at all; Canada, several ASTM C1157-inspired Latin American markets, and Australia apply performance-based principles to varying degrees while retaining some compositional framing. Two recently published ASTM standards, C1912 and C1945, extend the performance route to supplementary cementitious materials and natural pozzolans respectively, with no compositional restriction on origin. Because this route sets no clinker floor, it is the one that can, in principle, qualify binders well below a 0.50 clinker factor.

The second route is the spread of dedicated product standards that, though still largely compositional, explicitly permit high clinker substitution. Europe shows both the historical constraint and the shift: the harmonised EN 197 and EN 206 framework has traditionally limited low-clinker systems in structural use, but CEN has since issued two non-harmonised standards for decarbonisation, EN 197-5:2021 and EN 197-6:2023, with a companion specification for natural pozzolana, EN 18314, in preparation under CEN/TC 104. Comparable dedicated standards, summarised in Table 2, now exist across very different markets, from India, Ghana, Cuba, Sri Lanka, and Brazil to the compendia of Mexico and Canada, alongside China's emerging evaluation infrastructure for green and low-carbon cement, taking effect in 2026. India is also revising its foundational concrete code IS 456, whose draft fifth revision moves durability design from a prescriptive to a performance basis. Collectively, these instruments show a growing recognition that low-clinker binders can be reliably specified across diverse regulatory traditions. As Table 2 makes clear, however, the permitted clinker factor varies region by region, and only a subset of these standards reaches or crosses 0.50. Moreover, countries with performance-based codes still represent only a small share of global cement production; the majority remains prescriptively specified.

Table 2. Regulatory instruments relevant to low-clinker binders, grouped by type. Performance-based specifications qualify a binder by what it does; dedicated product standards remain largely compositional but explicitly permit high substitution; design and concrete codes still govern admission into load-bearing use. Only a subset reaches or crosses a clinker factor of 0.50.

Region / Country	Standard (year)	Regulatory type	Key provision (substitution / clinker)	Reaches ≤ 0.50 clinker?
United States	**ASTM C1157**	Performance based cement spec	No compositional limits; binder qualified by performance only	Yes (no clinker floor)
United States	**ASTM C1912**	Performance based SCM spec	Performance specification for SCMs, no restriction on origin	Yes (enabling)
United States	**ASTM C1945**	Performance based SCM spec	Equivalent performance framework for natural pozzolans	Yes (enabling)
Canada	**CSA A23.1**	Performance principles (partial)	Performance-based with some retained compositional framing	Partial
Colombia, Ecuador, El Salvador, Guatemala, Peru	**ASTM C1157-inspired**	Performance principles (partial)	Performance principles applied to varying degrees	Partial
Australia	**AS 3972**	Performance principles (partial)	Performance principles with some compositional framing	Partial
Europe (CEN)	**EN 197-5:2021**	Dedicated product standard	CEM II/C-M and composite cement CEM VI	Yes (CEM VI)
Europe (CEN)	**EN 197-6:2023**	Dedicated product standard	Cement with recycled building materials	Depends on class
Europe (CEN)	**EN 18314 (in prep.)**	Dedicated product standard	Natural pozzolana cement (CEN/TC 104)	In preparation
India	**IS 18189:2023**	Dedicated product standard (LC3)	Limestone calcined clay cement, clinker as low as 50%	Yes (= 0.50)
Ghana	**GS PAS 5:2024**	Dedicated product standard (LC3)	LC3 and composite LC3-M, clinker as low as 50%	Yes (= 0.50)
Cuba	**NC 1340:2020**	Dedicated product standard	Ternary TQC-25/TQC-35: up to 40% calcined pozzolana + 15% limestone	Yes (≈ 0.45 to 0.50)
Sri Lanka	**SLS 1697:2021**	Dedicated product standard	Portland-composite cement, up to 35% mineral additions	No (> 0.50)
Brazil	**NBR 16697:2018**	Dedicated product standard	CP II-E 6 to 34% slag; CP II-Z 6 to 14% pozzolan; CP II-F 11 to 25% limestone	Higher substitution CP III/IV only
Mexico	**NMX-C-414-ONNCCE-2017**	Dedicated compendium	Progressive, performance-oriented high-substitution blends	Partial
Canada	**CSA A3000:2023**	Dedicated compendium	High-substitution blended and Portland-limestone cements	Partial

China	**GB/T 47096-2026; JC/T 2951-2026; GB/T 47617-2026**	Evaluation / footprint (2026)	Green-product evaluation, carbon footprint quantification, energy and carbon reduction	n.a. (not a clinker limit)
Europe	**EN 1992 / EN 206**	Design / concrete code	Historically prescriptive minimum cement and maximum w/b	Restrictive
United States	**ACI 318 / ACI 301**	Design / concrete code	Prescriptive, deemed-to-satisfy provisions	Restrictive
India	**IS 456 (draft IS 456:2025)**	Design / concrete code	Draft moves durability design toward a performance basis	Transitioning
International	**ISO 15673**	Design guidance	Guidance for low-rise structures in developing regions	Enabling (low-rise)

Notes. Verdicts refer to the clinker-to-binder factor that each instrument can accommodate: Yes = reaches or crosses 0.50; Partial = performance principles applied with some compositional framing; Restrictive = prescriptive limits that penalise low-clinker binders; n.a. = the instrument sets no clinker limit. Permitting a blended cement to exist is not the same as admitting it, at a reduced clinker factor, into load-bearing design, which the concrete and design codes still govern.

Permitting a blended cement to exist is, moreover, not the same as admitting it, at a reduced clinker factor, into load-bearing design, which the concrete codes still govern. Even where low-clinker product standards are available, the structural design codes governing load-bearing construction, together with the conservatism of specifiers, contractors, and insurers, continue to impede widespread adoption. The binding constraint has consequently moved, or will move, from what the standards technically permit to what practitioners are willing to specify. In the author's assessment, the immediate opening for low-clinker binders is unreinforced and lightly loaded construction. Roughly three-quarters of cement serves masonry mortar, plaster, block laying, and screeds, where 10 to 20 MPa suffices [83]. These uses can absorb heavily substituted low-clinker binders now, within existing frameworks and without corrosion risk. International codes confirm that C20/25 to C25/30 concrete is structurally adequate for low-rise buildings, and ISO 15673 gives explicit guidance for such structures in developing regions. For producers and developers the decisive trade-off is not peak strength but the balance between clinker reduction, construction pace, durability, and cost. Generating initial demand hinges on linking these binders to large public programmes, as in Kenya's Affordable Housing Programme [84] and Ghana's infrastructure projects, where the national LC3 standard GS PAS 5:2024 enables commercial-scale production [85]. Strategic procurement can signal confidence and create the market pull that overcomes prescriptive inertia, especially where reinforcement is not required.

8 Conclusion: challenges, gaps, and a way forward

Chemical activation is the most direct route to giving low-clinker cements, those with a clinker factor at or below 0.50, adequate early strength. Calcium-based activators, low-dosage alkali salts, and hybrid alkaline systems are all credible, provided each is judged against the net-benefit condition and its early-versus-late trade-offs, while newer routes such as nucleation seeding, alkanolamines, and waste-derived calcium from carbide slag can raise reactivity at low carbon cost, even if dosage sensitivity, durability, and scale-up remain open. The central argument of this letter is that making low-clinker cements work is less a search for one missing technology than a matching problem, in which the right activator is aligned with the locally available precursor and the intended application. Solving the chemistry is necessary but not sufficient: uptake depends equally on performance-based specifications that admit low-clinker binders and on the willingness of practitioners to specify them where such standards already exist.

Because a large and rising share of cement is now produced in the Global South, where demand will grow fastest, the near-term levers there are the locally abundant ones, namely calcined clays and natural pozzolans, industrial by-products where they exist, and disciplined chemical activation to bring sluggish precursors into service. Carbon capture, by contrast, is a genuine but geographically bounded lever, valuable for a shrinking Northern clinker base yet unlikely to scale quickly where capital and infrastructure are scarce. No single precursor works everywhere; success depends on matching local materials, from low-grade calcined clays and natural pozzolans to fly ash, coal gangue, steel slag, recycled concrete fines, and waste glass, to the activator and the application, and on the specifications that let them be used.

Three technical gaps stand out for low-clinker binders. First, the long-term durability especially carbonation-induced corrosion, alkali-silica reaction, and freeze-thaw resistance, is undercharacterised. Second, the interaction between activators and diverse supplementary materials is poorly understood, since low-grade clays and emerging by-products behave differently from pure metakaolin, and the field needs a clear guide linking precursor type to the most suitable activator. Third, net-carbon accounting is inconsistent, and high activator dosages can cancel the clinker saving. The pragmatic near-term plan is therefore two-tiered: deploy low-clinker binders now in unreinforced and lightly loaded concrete, where durability issues are less of a concern, while multi-year field-exposure studies of carbonation, chloride ingress, and corrosion across diverse climates build the

evidence base for reinforced concrete. Realising this potential will require coordinated progress on three fronts at once: the binder chemistry, the regional supply of precursors, and the specifications and professional practice that govern deployment.

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Muhammad Riaz Ahmad : Conceptualization, Methodology, Funding acquisition, Writing - original draft, Writing – review & editing.

Competing interests

The author declares no competing interests relevant to the content of this article.

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