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PERSPECTIVE ARTICLE

Why geopolymers and alkali-activated materials are key components of a sustainable world: A perspective contribution

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Abstract

This perspective article delves into the transformative potential of alkali-activated materials, acid-activated materials, and geopolymers in mitigating climate change and market challenges. To harness the benefits of these materials, a comprehensive strategy is proposed. This strategy aims to integrate these materials into existing construction regulations, facilitate certification, and promote market access. Emphasizing research and innovation, the article advocates for, increased funding to refine the chemistry and production of these materials, prioritizing low-cost alternatives and local waste materials. Collaboration between academia and industry is encouraged to expedite technological advances and broaden applications. This article also underscores the need to develop economic and business models emphasizing the long-term benefits of these materials, including lower life-cycle costs and reduced environmental impact.

Incentivizing adoption through financial mechanisms like tax credits and subsidies is suggested. The strategy also includes scaling up production technology, fostering industrial collaboration for commercial viability, and developing global supply chains. Educational programs for professionals and regulators are recommended to enhance awareness and adoption. Additionally, comprehensive life-cycle assessments are proposed to demonstrate environmental benefits. The strategy culminates in expanding the applications of these materials beyond construction, fostering international collaboration for knowledge sharing, and thus positioning these materials as essential for sustainable construction and climate change mitigation.

KEYWORDS
alkali activation, binders/binding, cements, chemical durability, microstructure

1 | PREAMBLE

The intense global focus is currently being placed on the need to reduce the environmental emissions profile of global society, with traditional “heavy industry” sectors such as cement/concrete, iron/steel, ceramics, and glass being highlighted in both policy-focused and technically-focused documents as facing particularly steep challenges to meet national and international “net zero” goals. Cement production is a key underpinning technology for industrial and social development, infrastructure provision, and overall human well-being and quality of life. Cement must be relatively inexpensive, scalable in production up to production quantities that are almost unimaginable to other industrial sectors (totaling several gigatonnes per annum worldwide), and useable under conditions ranging from technologically advanced factory settings to manual production of blocks, tiles, and site-mixed concretes. They must offer versatility and high durability, robustness to (mis)handling and (mis)formulation, and reliable technical performance both in bulk applications in construction, and also more specialized applications where engineered functionality adds value in more “niche” applications. Coupling these challenges together, it is clear that a toolkit of cement-type materials will be needed in the future to meet industrial and societal needs. This also necessitates the development and implementation of an appropriate (and mature) regulatory framework, as civil engineering construction in particular is an area governed strictly—and importantly—by standards and codes. These must also gain acceptance from the public because cement and concrete are such an accepted everyday part of life that they cannot simply be revolutionized without this being noticed, and the public needs to comprehend and agree that materials which are derived in many cases from by-products are actually as safe and quality-controlled as the manufacturers are claiming.

Researchers in the academy as well as in industry are making good progress in the industrial application of ultra-low emission cementitious materials. Such types of binders are now feasible technical solutions, including the application of geopolymers and related materials as a particular example of a promising class of materials that will be the focus of this article. These materials have the potential to reduce waste and emissions in cement manufacturing, and also to provide high-performance and scalable ceramic materials with lower emissions and costs than many conventional ceramics. Very recently, new pathways for the synthesis of geopolymeric and related cementitious matrices have arisen that do not involve the addition of highly concentrated alkaline solutions and appear more sustainable and affordable. We need to rethink the supply chain of precursor materials, the basic understanding of the microstructure correlation with durability studies, and the pathway to additional future commercial applications. Central to this is the ability to identify the opportunities where alkali-activated materials (AAMs) may be the best available solution—and conversely also the applications that are best filled by different types of materials—to provide fit-for-purpose sustainable cement in service of modern society. Even though alkali activation of different sources of aluminosilicate has been known for many years,[1–5] only more recently have these attracted the attention of the numerous researchers dedicated to sustainable processing and materials, which provides the key motivation for this contribution.[6,7]

2 | WHAT ARE WE SPEAKING ABOUT? DEFINITIONS OF ALKALI- AND ACID-ACTIVATED CEMENTS AND GEOPOLYMERS

Geopolymers are inorganic poly silicate-aluminate polymers or chemically bonded ceramics centered around the nominal formula $M_2O{\bullet}Al_2O_3{\bullet}4SiO_2{\bullet}11H_2O$, where M = group I element and the amount of water is variable, depending on the particle size and specific surface area of the aluminosilicate starting material. They are refractory, inorganic polymers formed from both aluminum and silicon sources containing AlO_4^{-1} and SiO_4 tetrahedral units, under highly alkaline conditions (NaOH, KOH, CsOH) at ambient temperatures. Therefore, they are a rigid, hydrated, aluminosilicate solid containing group I, charge-balancing cations which result in an X-ray amorphous, cross-linked, and acid-resistant 3-D structure.

The term "geopolymer" has different meanings in different scientific communities. In materials science geopolymers are made from kaolinite of composition $Al_2O_3{\bullet}2SiO_2{\bullet}2H_2O$ which is heated at ~750°C for sufficiently long to be converted to disordered metakaolin ($Al_2O_3{\bullet}2SiO_2$). After dehydroxylation, the metakaolin shows an increased pozzolanic activity, which has been appreciated since the Roman period. When mixed under high shear with water glass solution (e.g. of composition $M_2O{\bullet}2SiO_2{\bullet}11H_2O$), it undergoes dissolution, polycondensation, and precipitation to form a geopolymer solid where the silicate and aluminate tetrahedra are corner shared[8–17] with very recent[18] evidence of a few percentages of nonframework Al species acting in charge-balancing roles and, finally, that not all tetrahedra have four common corners.

In the civil engineering community, the term "geopolymer" is also (although rather imprecisely) used to refer to the product resulting from high shear mixing of an alkaline silicate solution with aluminosilicate precursors, for example, fly ash and/or ground granulated blast furnace slag. These are also called "alkali-activated binders", "alkali-activated cements" or variants of those terms. The solid binding phase formed is also disordered, but in the presence of sufficient calcium, its nanostructure is based on the calcium silicate hydrate (C-S-H) or C-(A)-S-H) binder phases which form in traditional Portland-type or pozzolanic hydraulic cements. In this structure, the silicate or aluminate tetrahedra form chains arranged in layers sharing only two or sometimes three corners, and separated by layers of $Ca(OH)_2$ and interlayer spaces.[19–23] The fully crosslinked "geopolymer" phases described in the preceding paragraph are also termed "N-A-S-H" or "K-A-S-H" by cement scientists, where N and K are the cement chemistry abbreviations for Na_2O and K_2O, respectively. Recently, it was suggested that a more appropriate term would be "N-A-S" instead of "N-A-S-H" since water in geopolymers typically merely provides a reaction medium instead of chemically binding to the structure.[24]

One main difference between Portland clinker-based cement and geopolymers is that geopolymers may be chemically stable up to temperatures as high as 1000°C, after which they can crystallize into ceramics if designed with appropriate compositions or into ceramics or glass-ceramics compositions. When composites are formed with metakaolin-based geopolymers as the continuous phase, some mechanical strength can be still retained after high-temperature exposure. Conventional cements, on the other hand, contain significantly more chemically bound water and so steadily decompose with increasing temperature, losing their mechanical strength above 500–700°C. Thus metakaolin-based geopolymers are made like cement but can behave like a ceramic, while conventional hydraulic cements remain limited in their higher-temperature performance (Figure 1).

The difference between molecular structures of alkali-activated cements and geopolymers is illustrated in Figures 2 and 3. The chemical definition of alkali-activated cements and geopolymers based on their molecular bonding is summarized in Figure 4,[21–23] which illustrates the difference between alkali-activated and acid-activated geopolymers, where both families achieve charge balance and consist of tetrahedral molecular units. Geopolymers can be thought of as inorganic polymers analogous to aluminosilicate glasses charge-balanced by cations or supervalent phosphate, but made by inorganic polymerization in highly alkaline or acidic conditions, without any high-temperature melting.

In the literature on acid-based geopolymers, studies have mainly focused on characterizing them as coming from different aluminosilicate sources such as natural (gibbsite-rich, hematite-rich) or synthetic metakaolins,[27] industrial by-products (fly ash) or natural materials (volcanic ash) in the presence of H_3PO_4. The reactivity of different types of metakaolin seems to have little influence on the domains of existence of these geopolymers, favoring the amorphous matrix by partial replacement of SiO_4 by PO_4 tetrahedra (–Si–O–P–O; –Al–O–P–O) and, eventually, $AlPO_4$ crystalline inclusions (Figure 1).[28] On the other hand, their reactivity seems to depend largely on their chemical composition (Al/P ratio and amorphous content).[29] Their microstructure also has an influence: according to Liu et al.,[30] a smaller particle size reduces the consolidation time and improves the final compressive strength of the geopolymer. The behavior of the different amorphous and/or crystalline phases present in metakaolin can modify geopolymerization, especially when the latter are dissolved. During geopolymerization,

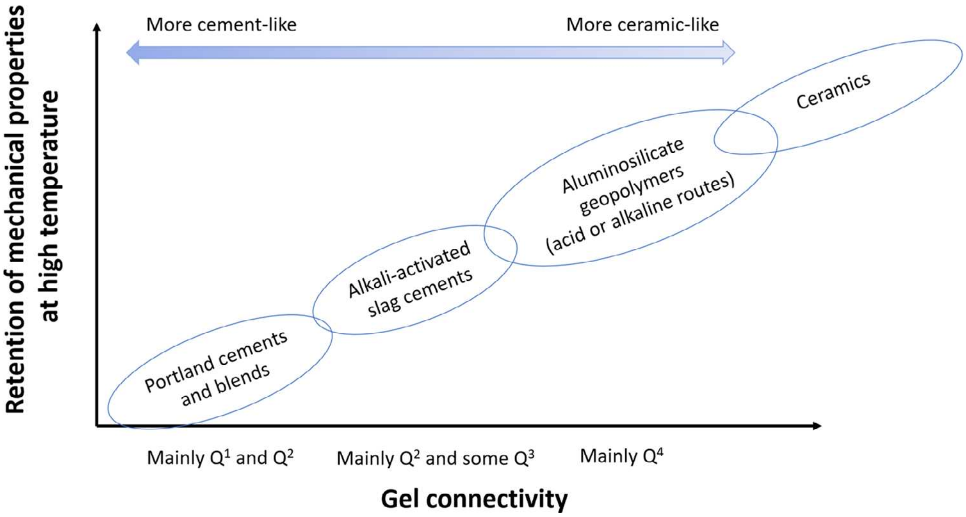

FIGURE 1 Schematic diagram of the relationship between conventional cement, activated materials/geopolymers, and ceramics. The Q^1, Q^2, Q^3, and Q^4 nomenclature describes the number of bridging oxygen atoms connected to a silicon atom (i.e., Q^1 and Q^2 are chain-like structures while Q^3 and Q^4 are 3-D networks).

quartz and anatase are not dissolved,[29] whereas gibbsite ($Al(OH)_3$)[31] and hematite (Fe_2O_3)[32] are dissolved, modifying the structure of the geopolymer. Tchakouté et al.[31] have also studied the effect of the gibbsite content of the kaolin before heat treatment. They proved that a high gibbsite content (γ-Al_2O_3 post-calcination) leads to a reduction in mechanical strength associated with a more heterogeneous microstructure.

The use of industrial by-products has also been tested in combination with metakaolin. In fact, these by-products alone do not allow the formation of geopolymers.[33] The main advantage of their addition is to accelerate consolidation (i.e., compressive strength) in the first stage of geopolymerization[34] achieving the same final performance as the alkali-activated formulations. The constituents of these ashes, rich in iron oxide, aluminum, calcium, and magnesium, dissolve in acidic media to form cations: Fe^{3+}/Fe^{2+}, Al^{3+}, Mg^{2+}, and Ca^{2+}.[35] This leads to the formation of additional phases in the material, such as brushite ($CaHPO_4{\cdot}2H_2O$), monetite ($CaHPO_4$), hematite (Fe_2O_3), and iron phosphate ($FePO_4$). More recently, some acid medium-based foams have been synthesized with highly insulating properties (61–75 mW x $m^{-1}K^{-1}$).[36]

The bulk-scale uptake of acid-activated materials (acid-AMs) in the construction sector appears likely to be rather limited in scope due to the relatively high cost of phosphoric acid as an activator, and also the lower compatibility of acidic materials with the established cement and concrete value chain (e.g., process equipment, reinforcing elements) which are generally designed for alkaline rather than acidic materials. Nonetheless, there appears to be the possibility for valuable usage of this type of material in specialist applications where the availability of the necessary materials enables their production at scale.

3 | WHAT ARE THE BARRIERS?

Alkali-activation technology is a mature technology that has been persistently penetrating the market as has been proven by some industrial companies providing products and solutions on the market. The launched products include concrete substitutes, bricks, fireproof foam, fireproof paint, sewage pipes, fiber-reinforced mortar for structural rehabilitation and surface reinforcement, among others.[37–42] Additionally, many research projects are underway to validate the technology on a pilot basis.[43–45] Intensive work is also underway to identify obstacles and barriers associated with their widespread adoption.

One of the major challenges is undoubtedly the complex chemistry already addressed in the previous sections. The wide variety of precursors and their complicated chemistry significantly affect the technical performance of geopolymers and alkali-activated products. The most studied precursors to date are metakaolin, class F fly ash, and ground granulated blast furnace slag, whose influential parameters have been identified.[46–49] The next problem is the limited and decreasing availability of some precursors—particularly blast furnace slag and also coal fly ashes in some regions. They are highly suitable as latent hydraulic or pozzolanic additives in cement and/or concrete but their availability will diminish by policy changes related to green transition such as switching from coal power plants to renewable energy sources and changing steel production into hydrogen reduction and electric arc furnaces. The availability of suitable precursor materials can be a critical factor in the successful implementation of the alkali-activation technology; hence, there is an ongoing search for alternative precursors

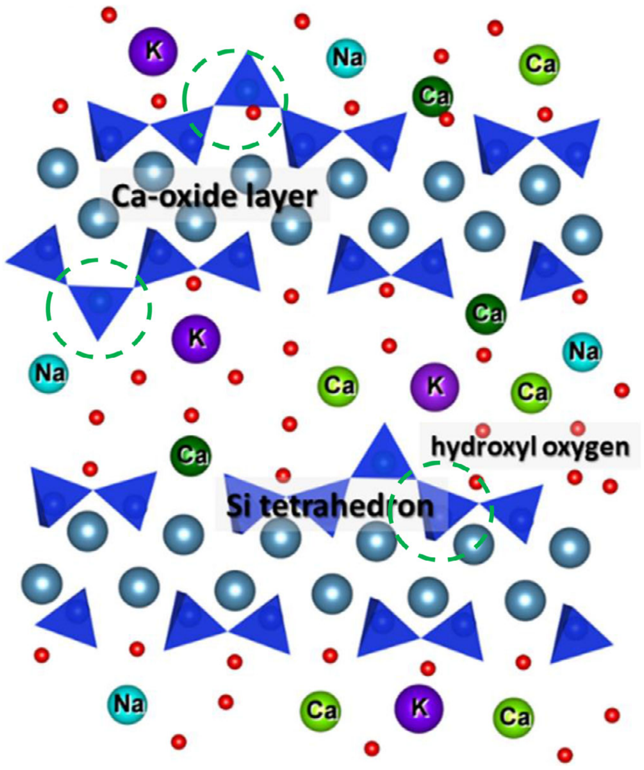

FIGURE 2 Schematic representation of the molecular structure of the C-A-S-H cementing phase as is formed in Portland-like, pozzolanic, or alkali-activated slag cement. The silicate tetrahedra (dark blue) are mainly in low-connectivity Q^1 and Q^2 environments; partial Al substitution is possible in the bridging tetrahedral sites (circled in green). Adapted from Miron et al.[25] under the Creative Commons CC-BY license.

and activators which includes various mine tailing slags, red mud, biomass ashes, construction and demolition waste, calcined clays, and more.[50–60] The valorization of widely available, aluminosilicate-containing mine tailings to make geopolymers is also a rich area of potential research. While utilizing such industrial wastes for useful products is a positive aspect, they also introduce new mineralogical and chemical aspects and compounds that can significantly affect the alkali-activation process. This could mean that the knowledge gained for the most studied precursors (metakaolin, blast furnace slag, or class F fly ash) is not sufficient to adequately design new mixtures. Therefore, each system requires a systematic study, including the long-term durability, to understand its chemistry. The technical suitability of the resulting products for their intended use must be demonstrated before marketing, which requires time and effort.

When working with waste materials, it is important to remember that they can significantly vary in their properties; this is especially true for waste generated from processes using different input materials, such as ash from co-combustion or from the combustion of different biomass types or incinerated sewage sludge, where the properties depend on the geographical location and/or the season. Hence, performance consistency is a key concern when using waste-based materials for alkali activation. In some cases, a mix design can be so robust that comparably large variations of the precursor properties still provide satisfactory outputs; for example, in applications with minimal requirements such as earth embankments or substrate layers.[61–63]

Key parts of the technical requirements also refer to safety during use and after the end of the product life cycle. This aspect is usually addressed by determining the leaching of heavy metals and selected organic compounds; the latter is usually not relevant to AAMs. Naturally occurring radioactive materials may also be a relevant consideration in some cases. The related requirements and test methods are currently not uniformly defined, neither in Europe nor worldwide. Sometimes these are stated in standards, but it should be taken into account that in most cases they depend on national requirements. Unless defined otherwise, an assessment according to the European Waste Framework Directive (WFD) can and should at least be performed, as products (even after some cycles of reuse or recycling) are landfilled at the end of their life cycle. WFD compliance prevents pollutants (potentially toxic elements or substances) from waste from entering the environment, where they may pose a risk to human health or the environment. This aspect is of great importance when hazardous waste is converted to AAM. It has also been shown that even inert materials (where heavy metal leaching is below the required limit) can sometimes exceed regulatory limits when used in alkaline-activated products. One reason for this may be improper mix design, but also the fact that some elements leach more readily in alkaline environments. Therefore, factors such as leaching must be carefully considered to ensure environmentally sustainable practices.[50,64–66]

A life-cycle assessment (LCA) also provides information parameters related to environmental aspects. It is widely accepted that AAM is much more environmentally friendly compared with Portland cement (PC) or ceramic materials on many (but potentially not all) criteria.[67] So far, much more information is available for different AAM systems, and in general, it is still possible to conclude that the environmental contribution of AAM is lower compared with the PC solutions, but there are some examples where the contribution of AAM to global warming potential (GWP) exceeds the PC best practices (Figure 5).[68] The main contribution of AAM to GWP is water glass when used, but also the necessary pretreatment of some precursors and/or curing at elevated temperatures.[69]

The next challenge for implementing the alkali-activation approach is technological: as production moves

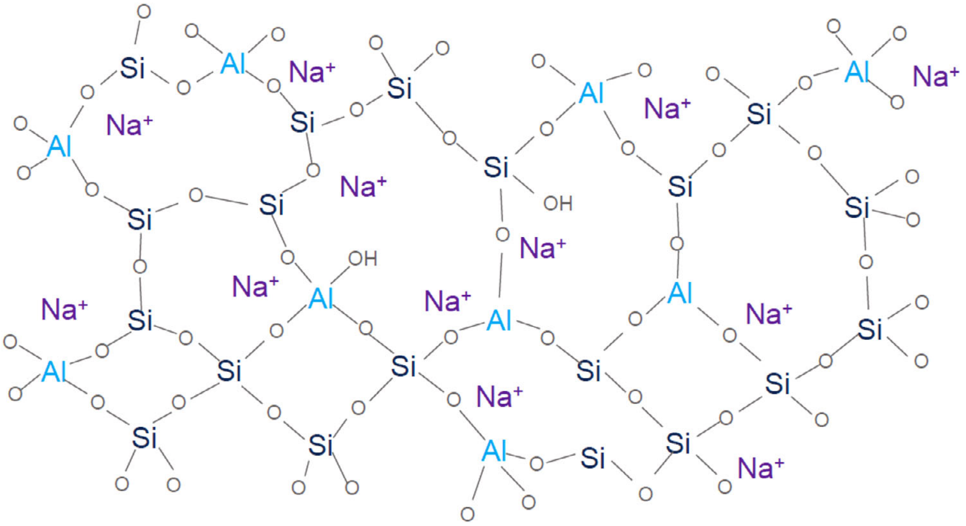

FIGURE 3 Two-dimensionally projected schematic representation of molecular structure of sodium-aluminosilicate geopolymer based on a structure where the majority of tetrahedra share four corners (Q^4). Some sites are sketched under-coordinated because the additional bonds are in the 3D structure, into or out of the plane shown. Molecular water is not shown. Redrawn and adapted from the structural models drawn by Barbosa et al.,[10] based particularly on the modifications to that model provided by Rowles et al.[26]

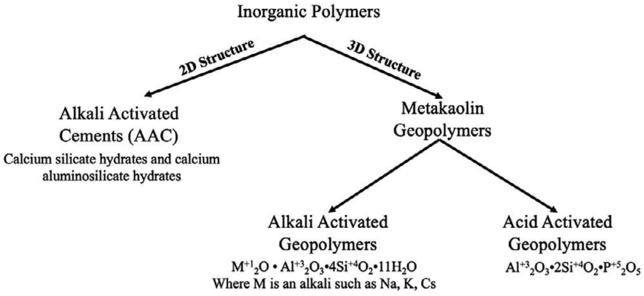

FIGURE 4 Distinguishing chemical definitions of alkali-activated cement and geopolymers based on their molecular network.

from laboratory conditions to larger scales, some drawbacks become apparent or more relevant. These can be cracking resulting from high shrinkage or inadequate drying/curing, sample warpage, and demolding problems.[66] As the manufacture of geopolymers and AAMs is significantly different from PC technology, its introduction requires investments in the technological process and personnel training. Special attention should be paid to occupational safety; alkali activation technology often uses highly alkaline solutions not used in conventional concrete, which may require special precautions.[47]

Additional constraints fall into socio-economic categories[70,71] which can hinder or even prevent the successful launch of innovative products unless properly addressed. For example, navigating the complex landscape of end-of-waste scenarios and complying with relevant legislation is a major challenge when upscaling a technology. If waste material can achieve secondary material status, it is easier to introduce in regular production. However, the process of obtaining this label is up to the waste holder. If the manufacturer of future construction products wants (or needs) to work directly with waste materials, special permits from national authorities are required, including leachate monitoring. Once the product is developed, it falls under a different regulation. The construction sector is strictly regulated at the EU level by EU Regulation No. 305/2011 Construction Products Regulation.[72] For most construction products, this is regulated in harmonized standards (hEN) which define the system of attestation of conformity and the CE mark. AAMs have not fallen within the scope of a hEN so far. Their legal access to the EU market is therefore regulated differently and should follow the European Technical Assessment procedure, which requires the preparation of a corresponding European Assessment Document defining the relevant essential characteristics. Alternatively, products may be placed on the market in accordance with national regulations.

There aren't any standards for AAMs in the USA either, but the American Concrete Institute's structural code, ACI 318–19 (Building Code Requirements for Structural Concrete), includes provisions for an "alternative cement" that can be used as a direct replacement for conventional cementitious materials. This code allows for the use of alternative cements—which could potentially include AAMs—to be approved on a case-by-case basis if they are deemed acceptable by the relevant authorities. In some other parts of the world, the situation is somewhat more favorable, such as in Australia, where strong industrial players entered the market with AAM products, such as Zeobond Pty Ltd. in Victoria or Wagners, later followed by other suppliers. Special approvals were

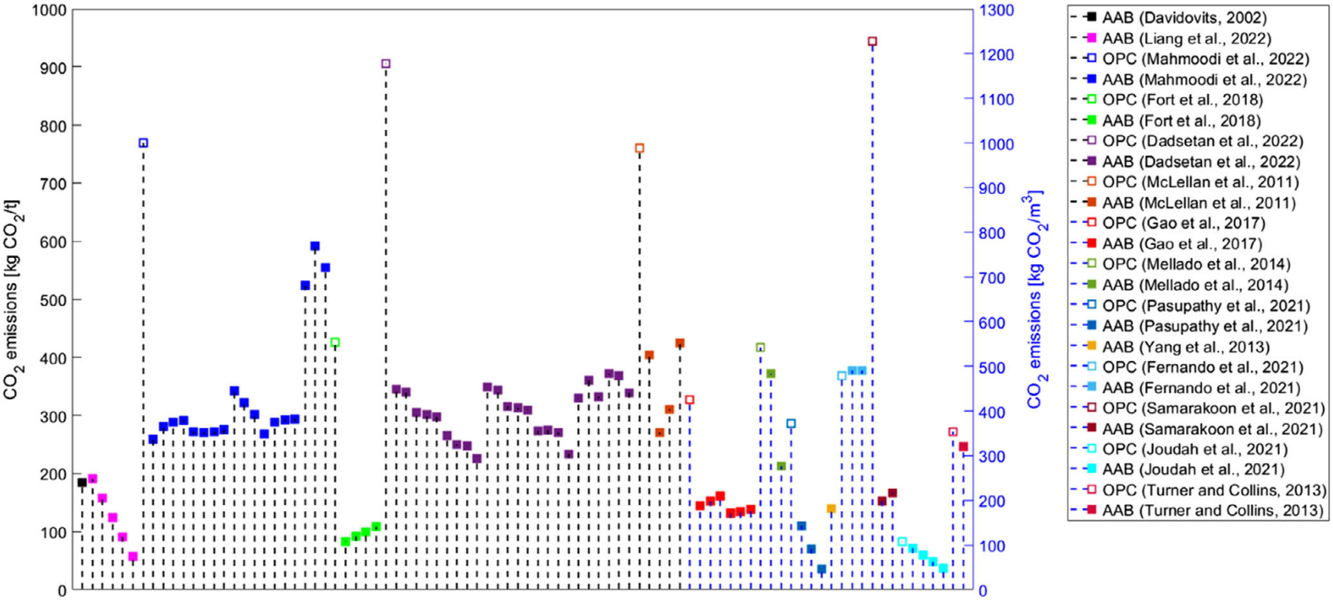

FIGURE 5 CO$_2$ emissions of alkali-activated materials from the literature (68 - under the Creative Commons CC-BY license).

granted by regulators for the first project-specific applications, which required close collaboration between technology providers, regulators, civil engineers, and asset owners. Over time, as confidence in AAM grew, the need to develop new specifications and standards or extend the existing framework to enable AAM was recognized, resulting in Australian Technical Specification 199:2023: Design of geopolymer and alkali-activated binder concrete structures,[73] to be used in conjunction with Australian Standard AS 3600:2018: Concrete Structures,[74] and Australian Standard AS 3582.4:2022: Supplementary Cementitious Materials Part 4: Pozzolans—Manufactured.[75]

In any case, the lack of uniformly recognized standards for AAMs is an obstacle to marketing. At the very least, it takes longer to obtain the necessary documentation, and it may also cost more than if standards existed. Developing standards for alkali activation processes and AAMs therefore remains an ongoing task.

From an economic point of view, the precursors (mainly wastes) generally have relatively low costs (apart from the effort to obtain permits and the pretreatment that is sometimes required). One exception is metakaolin, which is generally not a waste. For example, comparing the price of producing 1 ton of OPC concrete, 1 ton of AAM based on slag and soda as activators, and 1 ton of AAM based on metakaolin, water glass, and hydroxide, the prices are \$100, \$100, and \$550, respectively (data for the USA[76]). The activators (e.g., water glass or hydroxide) represent the largest contribution in the life cycle analysis and in the LCA. As shown in Figure 6, AAMs have not yet been economically competitive. In most cases, AAMs are still more expensive PC solutions. However, cost is a relative category; while the technical performance of AAMs remains the same regardless of when they are produced, costs can increase or decrease dramatically over time (depending in particular on policy incentives or taxes related to carbon footprint).

In any case, the price may be a barrier to widespread adoption, and strategies for low-cost production or identification of activators from waste streams are needed. It is important to note that the activators that are currently available on a large scale are generally produced at high purity for applications in chemical and other processes that require this purity, where high purity is often not essential for their use as alkali activators.

Last but not least is the issue of social acceptance; it has been widely recognized that there are some hesitations about accepting recycled products. Gaining public and professional acceptance by obtaining a widespread understanding of the alkali activation processes and by providing transparent information about any potential drawbacks is critical for their successful integration into mainstream construction practices.

Each obstacle and barrier requires specific action and often a tremendous amount of work to overcome. In this context, research and pilot projects are of great importance. In particular, pilot projects at TRL 5 (note: a TRL (Technology Readiness Level) of 5 indicates a technology validated in a relevant environment) and above are of paramount importance in advancing the alkali-activation technology and identifying real-scale challenges so that potential manufacturers can successfully address them. This approach and support by financial incentives can fully realize the potential benefits of alkali activation and make

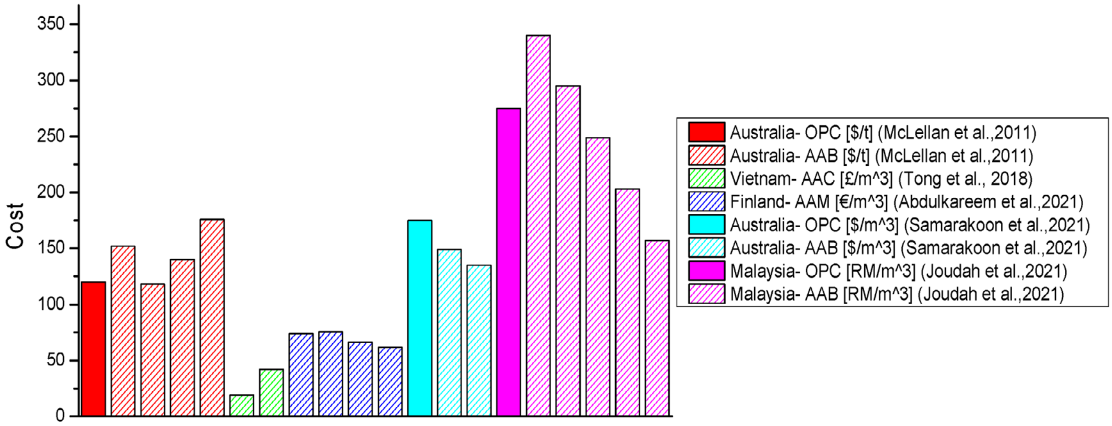

FIGURE 6 Economic performance of alkali-activated materials from the literature (68 - under the Creative Commons CC-BY license).

it an important pillar in the transition from a linear to circular economy in the construction sector.

4 | WHERE TO GO: NEW PERSPECTIVE

4.1 | Building materials

The global construction sector is rapidly understanding toward the ways (and needs) to control the emission of atmospheric pollutants, while still providing society with the high-quality building materials needed to support a high standard of living. So, attention has fallen on alkali activation as an important part of the available toolkit of cement production techniques.[77] This interest is supported by rapid advances in fundamental scientific understanding,[78] as well as engineering advances that include improved know-how around how alkali-activated concretes can be controlled in the fluid state to enable them to be handled and placed safely and reliably. These advances in reliability and confidence are also being mirrored in parallel industries, for example, there are large-scale industrially-focused research and development programs underway to use geopolymer or alkali-activated cements in the immobilization of nuclear wastes.[79] This is a process that requires intricate control of material characteristics, with very high consequences in the case of material or process failures, and so the fact that this class of materials is under serious discussion (and actual implementation in some countries) for this application highlights the advancements that have been made.

Nonetheless, there are still some important opportunities for advancement in a practical sense; these include the following points which may be highlighted:

- First and foremost, the materials need to be matched to the applications. Innovative materials are best suited to use in applications where their technical properties are important to achieving the desired outcomes—which can showcase the potential of the materials in a broader sense—but also where the consequences (financial or safety) of any possible material failures are as low as possible. It is neither desirable nor necessary to construct the most safety-critical mechanically-loaded elements in a structure from a “new” material; the bulk of the environmental and sustainability benefits can be gained from focusing new materials into parts of a structure or system where the volume of concrete is relatively high and the structural demands placed on it are relatively low. This may include cases such as paving or foundations, and also concrete products (blocks, pipes, tiles). This reinforces the discussions above regarding the importance of understanding and controlling leaching of alkalis and other potential contaminants from the binder structure, particularly if waste-derived precursors are used, as many of these applications are exposed to groundwater or rainwater.
- The mechanical characteristics of alkali-activated and geopolymer concretes, in particular the modulus of elasticity, Poisson’s ratio, flexural and tensile strength, and creep—and the relationships between each of these quantities and the compressive strength (which is generally much easier to measure) need to be investigated and validated for use in structural calculations based on standard (or adapted) codes.
- Related to this point, the existing international movements toward standardization of non-Portland cements—including but not limited to the materials that are within the scope of this article, and largely based on performance principles rather than in the form of traditional prescriptive standards—are providing important opportunities for large-scale practical application. It is timely to mention here in particular the Standards Australia Technical Specification SA

TS 199:2023,[80] the ASTM International testing standard C1928 for alkali-activated mortar cubes,[81] and the British Standards Institute BSI Flex 350,[82] which have all recently been published and offers important support and insight to potential specifiers and end-users. Additional initiatives are also ongoing in ASTM International,[83] among others, as example in South Africa, SANS 10100: 2014 has allowed a performance-based specification to allow the use of zero PC ash or ground granulated blast-furnace slag-based concrete to be used on industrial scale, accounting for the first application on a commercial project in 2013.

- Technical advances are still clearly needed in areas including mix formulation and the role of additives; sustainable and low-cost provision of activators; appropriate and accurate durability testing methods; and many other aspects required for validation of long-term performance. However, the continuing need to advance in these areas should not be seen as shortcomings in the current understanding of the materials. Geopolymer and alkali-activated cements should now be considered sufficiently mature for implementation and deployment at scale, with a strong scientific underpinning, even though more research is needed (and is ongoing, and must be further supported by funders and commercial partners) to further advance and optimize the materials and technology.
- Finally, environmental performance of these cements, and the concrete and mortar products that can be made from them, needs to be more fully validated through improvements in life cycle inventory data,[67] more specific assessment protocols including accurately drawn scopes for each specific case, inclusion of service life and recyclability in emissions calculations, and accurate and realistic benchmarking against established solutions.

4.2 | From construction materials to high-end technical applications

The potential precursors and activator components for geopolymers and AAMs include many materials with a waste status, which means that their net economic value is negative (in Europe, less than approx. −100€/ton, depending on the classification of waste) due to the landfilling gate fees and taxes. Taxes are not stable; they increase from year to year, partly due to the annual consumer price index, but also to encourage recycling. To get a general idea of the taxes, the references given provide an overview of taxes of waste landfilling in Europe.[84,85] It should be noted that some potential waste materials have been also banned from landfilling (e.g., construction and demolition waste.[86] It has been observed that increasing landfill taxes and bans may cause waste to be diverted for combustion and energy recovery instead of recycling as material.[87] However, incineration to recover energy is not generally possible for waste suitable for geopolymers and AAMs since they are incombustible inorganic fractions. Thus, landfill taxes, bans, and gate fees create a strong incentive to upcycle waste toward higher positions on the waste hierarchy where geopolymer and alkali-activation technology provide highly feasible solutions for inorganic waste.

As discussed above, by developing binder materials for construction, their value can be upgraded to a level of approx. 10–100€/tonne, which roughly represents the price range for aggregates and PC (see Figure 6). However, by applying geopolymer or alkali-activation technology it is also possible to develop high-end products, with their economic value being further increased by at least one or two orders of magnitude higher in comparison to binders in construction. The higher price of the final product may enable the utilization of precursors formed in lower quantities, more complex pre-treatment of raw materials, and use of alkali-activator or other chemicals not possible in the case of concrete binders.

In the context of high-end products, some appealing features of geopolymers and AAMs include flexible, simple, and low-energy preparation process, potential for low cost and better environmental profile, and promising technical performance in comparison to many competing materials, such as synthetic zeolites, high-temperature ceramics, or certain organic polymers.[88,89] These factors enable the fabrication of foams, granules, disks, or 3D-printed lattices with controlled porosities and other properties, which might be difficult with many other materials[90–92] Both low- and high-calcium materials (i.e., zeolite- and tobermorite-like aluminosilicates, respectively) have been studied by utilizing their intrinsic properties (e.g., mesoporosity or cation-exchange capacity) or by modifying the materials (e.g., introducing transition metals, developing composites, or adding organic functional groups to the surface).[93,94]

One relatively early publication related to the high-end applications of geopolymers and AAMs was by Kunze et al.[95] describing radium adsorption from water by using a barium-modified AAM. Since then, geopolymers and AAMs have been studied for example for the adsorption of various toxic metal(loid)s, nutrients, organic dyes, radioisotopes, water hardness, and rare earth elements.[96] Many recent studies aim to simulate realistic (waste)water treatment conditions (e.g., Roviello et al.[97], Gonçalves Nuno et al.[98]), evaluate the regeneration of the adsorbents (e.g., Medri et al.[99]), or report pilot-scale experiments (e.g., Laukkanen et al.[100]). In addition, the development of synergistic composite structures for adsorption with for example graphene oxide, carbon nanotubes, or cellulose nanofibers has become an active research area (see e.g., Selkälä et al.[101], Yan et al.[102], Yan et al.[103]). For geopolymer or alkali-activated adsorbents, several patents have been published[104] demonstrating that there is also commercial interest for these materials.

Another active research topic is the use of geopolymers and AAMs as heterogeneous catalysts or catalyst supports in oxidative wastewater treatment,[96] air pollution control,[105] or chemical processes.[106] Here, some interesting properties include the Lewis and Brønsted acid sites of the materials and the ease of introducing catalytically active metals via substation or ion-exchange.[107] In wastewater treatment, the targeted application is to abate organic micropollutants via advanced oxidation processes (i.e., enhanced formation of radicals) such as photocatalysis,[108] catalytic wet peroxide oxidation,[109] or peracetic acid-based oxidation.[110] In terms of air pollution treatment, the studied applications include oxidation of volatile organic compounds, reduction of nitrogen oxides, adsorption of CO_2, and separation of particulate matter.[111–114] For chemical processes, the possible applications are varied, for example, Beckmann rearrangement, Friedel-Crafts alkylation or acylation reactions, biodiesel production, and hydrogen production.[109]

With geopolymer or alkali-activated membranes and membrane supports, the target is to obtain similar properties as with ceramic membranes (e.g., enhanced service life over organic polymer membranes) but with clearly reduced costs.[115] Promising results have been obtained when using geopolymer and AAMs in micro- or ultrafiltration pressure area to separate suspended or dissolved solids (e.g., [116,117]). Another reported application is the pervaporation of water/ethanol.[118] What is especially interesting is that the cost of geopolymer or alkali-activated membranes can be just ∼2% of that of a comparable ceramic membrane[119] (which can be approx. 10 times that of an organic polymer membrane[120]).

There is also a rapidly increasing number of other innovative high-end applications for geopolymer and AAMs in which the development is in the early stages of research. These include environmental technology applications such as pH regulating materials for anaerobic digestion,[121] biofilm carrier media for bioreactors,[122] and water filtration and disinfection.[123,124] In agriculture and plant cultivation, geopolymers could find applications as a coating material to develop controlled-release fertilizers[125] or plant substrate.[126] In the medical field, geopolymers have been proposed for controlled-release drug delivery (for e.g., opioids[127] or the COVID-19 drug niclosamide.[128] The antibacterial properties of different types of geopolymers have been also investigated, including discussion in relation to their potential cytotoxicity to mammal cells.[129–132] Porous aluminosilicate geopolymers have been investigated to remove cytotoxic agents from biological environments, specifically focusing on macroporous and mesoporous geopolymers[133] and their effect on their inhibiting capacity against Gram-negative bacterial strains (*Escherichia coli*) and Gram-positive bacterial strain (*Staphylococcus aureus*).

There is also an expanding area of potential applications of geopolymers as implant materials and for bone regeneration, as reviewed in the literature.[134] Special attention has received the design of geopolymers with properties suitable for bone tissue engineering, for example, combined with hydroxyapatite and other calcium phosphate ceramics,[135] and for dental restorative materials.[136,137] On the other hand, applications of geopolymers in contact with the human body have also raised concerns, particularly regarding potential toxicity, pH variation effects, and low osteoconductivity. An alternative to tackle such issues is the formulation of composite or hybrid geopolymer systems, for example, combined with bioactive ceramics, glasses, and biopolymers. In this context, several techniques available to produce porous geopolymers can be exploited for their biomedical applications, especially for bone tissue scaffolds which require highly porous structures.[138] Certainly, the investigation of the applications of geopolymers and their composites in the biomedical field is in its infancy, and it can be anticipated that more efforts by the geopolymer research community in collaboration with biomaterials scientists will lead to advances in the field.

In analytical chemistry, geopolymers are a potential stationary phase for liquid chromatography due to their different selectivity compared with existing phases and stability at different pH conditions.[139–141]

Finally, there are also several proposed applications utilizing the electrical properties of geopolymers or AAMs: electrode materials for structural supercapacitors[142] and microbial fuel cells,[143] solid-state battery electrolytes,[144] and dielectric materials for antennas.[145] In many of the mentioned technical applications, beyond construction materials for which parts of simple shapes are required, components of intricate or complex shapes are usually necessary. In this case, geopolymer or AAM processing routes hold out the promise of near net-shape (or even precise net-shape) fabrication as many formulations are 3D printable.[91,98,146] In addition, the postfabrication machining of geopolymer components, including drilling, cutting, grinding, and surface polishing, to obtain the required component shape, has been investigated only in a few previous studies (e.g., Toniolo et al.[146]) and requires therefore further attention.

Thus, it can be concluded that new potential applications for geopolymers and AAMs are being proposed actively. Key aspects in this area to future development include developing yet more advanced preparation and material modification methods, aiming for milder reaction conditions (e.g., less concentrated alkali-activators via the use of ligand-assisted geopolymer formation), and deeply understanding the connection between the material properties and performance in the aimed applications.

5 | A FEASIBLE SCALE-UP FUTURE

Increasing awareness of the potential impact of human activity on climate change generates demand for concrete with low embedded carbon emissions. The term “low carbon cement” (LCC) has become mainstream at most conferences on cement/concrete engineering. Nevertheless, LCC could mean anything and often refers to PC blended with 30%–40% supplementary cementitious materials (SCM). “Green washing” is prevalent in the concrete industry, so it is not evident in the market what products are truly LCC. With the push toward LCC and support at political and community levels, AAMs and other true LCC products should be adopted widely in the market, which is unfortunately not the case. With the term LCC now mainstream, the obstacles toward adoption of LCC with ultra-low carbon emissions are subtler than in the past.

The PC industry has no intent to change its value chain and it plans to continue using its existing infrastructure of clinker production coupled with carbon capture and sequestration, as well as blending with SCM.[147] With decarbonization of electricity generation and steel production, coal fly ash (CFA) and blast furnace slag (BFS), which are already in short supply, will be phased out gradually. Therefore, the PC industry views limestone-calcined clay cement (LC3) where 50% of clinker is replaced as the cement of the future. With carbon capture and the use of renewable or nuclear energy, the PC industry aims to achieve net zero emissions, assuming that the substantial additional cost of cement production will be borne by the market. There may be some use of sodium sulfate as an activator while BFS is still available, but the PC industry does not view AAMs as a future solution.

In several jurisdictions like the European Union, LC3 and blended PC cement can now be used within the existing EN standard framework. While it usually takes years to change cement and concrete standards, it is no surprise that with the support of the PC industry, the standards have been revised quickly to allow for LC3 in several jurisdictions. In contrast, several standard frameworks remain partly prescriptive by specifying minimum clinker content. The EN framework with its multiple classes remains largely prescriptive and still does not allow for radical innovation in cement and concrete production, hence this framework protects the incumbents and presents a barrier for alternative technologies like alkali-activation. The new Australian standard for AAM or geopolymer structural concrete overcomes this barrier to some extent but still has implicit constraints based on what is deemed to be AAM practice.[148]

If the construction industry is serious about innovation and carbon reduction, it needs to move toward a complete performance-based standards framework. The EN system with its multiple classes is a hybrid of prescription and performance-based standards. Even the structural code for blended concrete in Australia (Australian Standard 3600) has implicit prescriptive features when the aim was to make it more performance-based. Sutter and Hooton[149] outline the deficiency of the current standards regime and why a prescriptive approach is outdated, but at the same time why it remains a challenge to progress toward a performance-based approach.[149]

A key reason for the industry to continue with prescriptive standards is that it is easier to outsource risk. Provided a cement or concrete supplier can demonstrate that they have conformed to a prescriptive standard, they have more grounds for defense in a lawsuit where there is structural failure. In contrast, if standards are performance-based, the division of liability between cement production, concrete production, concrete placement, and structural design is less evident. That is one reason why the construction industry is segmented so that risk is more constrained. Vertical integration of the source material supply chain, concrete production, and construction activity largely overcomes this challenge by internalizing risk. Unfortunately, such a shift in culture and organization in the construction industry is seldom articulated and acts as an obstacle to advance performance-based standards as well as carbon reduction.

The ongoing debate about laboratory test methods to quantify the durability and service-life of AAM and other true LCC presents a hurdle that the AAM and LCC community must address as a matter of urgency. There is a natural role for academic research in collaboration with industry to address this gap in our knowledge. If we are serious about carbon reduction and the use of more secondary resources in construction, we need to develop and obtain wide acceptance of such durability methods. We do not have the luxury of waiting decades before we can validate our laboratory methods in field testing, and therefore we need to have methods with a sound mechanistic basis. Increasingly, test methods for concrete permeability are being accepted for AAM and LCC as predictors of service-life. In contrast, there remains a debate about general test methods for binder phase stability, because the tests must be tailored to the exposure conditions and the binder chemistry.

A related subject that has received much attention in the literature but that has not yet been resolved is the relatively high carbonation rate of AAM and LCC,[150,151] while some in-service sampling has shown a weak relationship between accelerated carbonation testing and natural carbonation.[152] More importantly, high carbonation has been demonstrated to not always cause rapid corrosion of steel reinforcement.[153] Instead of measuring carbonation rate and/or chloride diffusion as predictors of steel corrosion, it is suggested here that actual steel corrosion is measured in carbonated concrete as a more accurate predictor of service-life. In such tests, it remains a challenge to relate laboratory measurements to service-life, which should be an active area of academic research.

Despite the above obstacles, it has been possible to get wide adoption of AAM and true LCC in Australia. There is wider acceptance of performance-based standards by structural engineers and road authorities that are pivotal in approving concrete for major public infrastructure. A remaining hurdle is that these authorities usually insist on having mixed designs disclosed, which is not possible for reasons of protecting intellectual property. In the medium term, while using existing sources of SCM like BFS and CFA available in the cementitious supply chain, a commercial strategy may involve a production of pre-mixed and pre-cast concrete at existing facilities on a licensing basis. In the longer term, new reactors will be developed to produce synthetic SCM from virgin and secondary sources, without reliance on BFS and CFA. Such reactors producing ultra-low CO_2 cementitious material will unlock new value chains independent of the PC industry.[154]

6 | CONCLUSION

Turning the challenges and uncertainties surrounding AAMs, acid-AMs, and geopolymer materials and technologies into market and climate change opportunities requires a holistic and strategic approach.

Policy, standardization, and regulatory alignment and engagement, consisting of working with regulatory bodies to develop and adopt international standards for AAMs, acid-AMs, and geopolymers that will facilitate market access should serve to advocate for the inclusion of these materials in existing building codes to streamline evaluation and certification processes. In addition, lobbying for policy reforms is critical to recognize and incentivize the use of alkali-activated, acid-activated and geopolymer materials. Furthermore, engagement with policymakers to clarify end-of-waste criteria is essential, as this will facilitate the classification of secondary materials, thus facilitating the transition from waste to valuable construction inputs.

Investment in research and innovation should prioritize funding for research and development to streamline the chemistry and production processes of AAMs, acid-AMs, and geopolymers. This includes reducing reliance on expensive raw materials and activators and exploring lower purity, lower cost alternatives. There is also a need to increase R&D funding to refine alkali-activated, acid-activated, and geopolymer formulations using local waste materials.

It is also important to encourage partnerships between academia and industry to drive technological advances and discover new applications. Attention should be given to the development of robust mix designs that can adapt to the varying properties of waste materials and ensure consistent and reliable performance. Finally, conducting long-term durability studies is essential to establish a solid foundation for the reliability and safety of AAMs, acid AMs, and geopolymers.

To underscore the long-term benefits of these materials, it is critical to create economic models. These models should highlight not only the immediate benefits but also the long-term benefits of these materials. In addition, it is important to develop business models that take advantage of the low cost of waste materials. These models should highlight the economic benefits of AAMs, acid-acid-AMs, and geopolymers. Emphasis should be placed on their lower life cycle costs and reduction in environmental impact fees, making them financially attractive options.

Furthermore, exploring and introducing financial incentives for companies that adopt sustainable materials is essential. These incentives can take various forms, such as tax breaks, grants, subsidies, tax credits, and carbon credits. Such incentives would encourage the adoption of alkali-activated, acid-activated, and geopolymer materials, supporting a shift toward more sustainable construction practices.

Technology scaling, commercialization, and industrial collaboration Technology involves several key strategies. Partnering with industry players to establish large-scale production facilities that serve as a platform to demonstrate the commercial viability of new technologies is essential. Sharing best practices across the industry is essential to standardize processes and ensure safety protocols, particularly in the handling of raw materials. Investing in the scale-up of production technology is essential to improve market competitiveness. In addition, encouraging joint ventures or partnerships can be an effective way to pool resources and expertise, significantly reducing financial risk for individual companies.

Supply chain development requires the establishment of global networks for raw materials. This ensures that industries are able to source necessary components and overcome regional differences in availability. It also involves encouraging the identification and use of alternative precursors and raw materials, helping to streamline resource management.

The implementation of educational programs for industry professionals and regulators is critical. These programs are designed to increase awareness of the benefits of alkali-activated, acid-activated, and geopolymer materials. In addition, there is a focus on stakeholder engagement in the construction industry. This engagement is key to promoting the adoption of these materials and addressing any concerns related to their performance and applications. Furthermore, the importance of providing comprehensive training to construction industry professionals is recognized. This training will cover the proper handling of alkali-activated, acid-activated, and geopolymer mortars and concretes, including pouring and other related procedures.

It is also important to conduct comprehensive LCAs to highlight the environmental advantages of alkali-activated, acid-activated, and geopolymer materials over traditional construction materials. These LCAs are also used in our marketing and promotional efforts to showcase the positive impact of AAMs on efforts to mitigate climate change.

The market expansion strategy includes expanding the applications of alkali-activated, acid-activated, and geopolymer materials beyond the construction sector to other industries. This will be achieved by developing and marketing new products based on these materials, specifically tailored to meet the unique needs of different industries. The goal is to create and develop niche markets with these specialized products.

International cooperation will require the promotion of global cooperation and the sharing of knowledge and best practices. This initiative aims to create a platform for sharing knowledge on applications, benefits, and case studies related to alkali-activated, acid-activated, and geopolymer materials. The goal is to create a global community of practice. It is recommended that institutions such as The International Union of Laboratories and Experts in Construction Materials, Systems and Structures take a more active role in this endeavor.

By implementing these strategies, the industry can not only overcome the barriers to adoption of alkali-activated, acid-activated, and geopolymer materials but also position these materials as essential to sustainable construction practices, thereby making a significant contribution to the fight against climate change and supporting market growth.

The following examples, among others, may illustrate a trajectory where geopolymer and AA materials, through entrepreneurial foresight and initiative, progress from academic and industrial obscurity to wide-ranging market application and acceptance.

1. Pyrament Cement: As the first geopolymer developed for industrial applications in the 1980s by Davidovits and Sawyer for Lone Star Industries, it laid the groundwork for academic research transitioning into practical, marketable solutions.[155]
2. Earth Friendly Concrete: developed by Wagners (AUS) as a new generation building material designed to reduce embodied carbon.[156] Cases related to EFC:
   - Pinkenba Shipping Wharf: The wharf's deck consists of 191 prefabricated panels that span between 8 and 12 m over steel headstock beams.
   - The University of Queensland's Global Change Institute: This building represents a landmark in geopolymer application, being the world's first to employ structural geopolymer concrete in public architecture, symbolizing a successful scale-up from experimental to commercial use.
   - Brisbane West Wellcamp Airport: As an example of green construction, the airport used over 30 000 cubic meters of Wagners' EFC, marking it as the greenest airport in the world at the time and illustrating the scalability of geopolymers for large infrastructure.
3. E-Crete: developed by Zeobond, a company founded by Prof. Jannie van Deventer.[157] The concrete was applied in a number of venues in Australia (Lyndarum Estate, Westgate Freeway, Highlands Craigieburn, to name a few).
4. Geopolymer International: Led by William Hoff, the company develops compositions of AAM to fulfill customers' demands, builds large-scale 3D printers for construction works, and actually is building houses in South Carolina (USA) using a proprietary composition of AAM and an innovative 3D-printing technology (https://geopolymerinternational.com/about-us/).
5. GeoSpray by Milliken: This innovative product for sewage tube repair demonstrates the utility and environmental benefits of geopolymers, providing a sustainable solution for infrastructure maintenance and repair.[158]
6. Formula 1 Application: The use of carbon/geopolymer composites for thermal shielding by the Benetton-Renault team, and the geopolymer-composite exhaust pipe system developed by Porsche, showcase the high-performance application of these materials beyond the construction sector.

These examples, among others, illustrate a trajectory where geopolymer and AA materials, through entrepreneurial foresight and initiative, progress from academic and industrial obscurity to wide-ranging market application and acceptance.

AUTHOR CONTRIBUTIONS

All the authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

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