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Alkali-activated materials

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Abstract

This paper, which forms part of the UNEP White Papers series on Eco-Efficient Cements, provides a brief discussion of the class of cementing materials known as 'alkali-activated binders', which are identified to have potential for utilization as a key component of a sustainable future global construction materials industry. These cements are not expected to offer a like-for-like replacement of Portland cement across its full range of applications, for reasons related to supply chain limitations, practical challenges in some modes of application, and the need for careful control of formulation and curing. However, when produced using locally-available raw materials, with well-formulated mix designs (including in particular consideration of the environmental footprint of the alkaline activator) and production under adequate levels of quality control, alkali-activated binders are potentially an important and cost-effective component of the future toolkit of sustainable construction materials.

1 Introduction

Alkali-activated binders have been widely discussed and promoted as a component of the current and future toolkit of 'sustainable cementing binder systems' [1-7]. These binders, sometimes also named 'geopolymers' [8], can be generated from a wide range of aluminosilicate precursors, with differing availability, reactivity, cost and value worldwide. For this reason, alkali-activated binders are far from a one-size-fits-all solution to meet future construction materials needs in a manner similar to the use of Portland cement. However, this diversity does mean that this class of materials is very versatile and locally adaptable, and thus likely to form a key component of a broader toolkit of cements used worldwide in the development of a sustainable future construction materials industry.

The key factor which is likely to determine the likelihood of uptake and utilization of alkali-activated binders in any specific location is the local availability of suitable raw materials (precursors and activators). Many of the precursors which are used to produce alkali-activated binders are also in demand for use in blends with Portland cement, and this competition for raw materials must also be taken into consideration in any discussion of the supply chains related to alkali-activated materials. If alkali-activated materials are to be promoted as an environmentally beneficial option, the transport of bulk materials must obviously be minimized, as this can dominate the emissions footprint of the binder as a whole if materials must be transported long distances [9]. This therefore brings a focus on the development and utilization of locally available materials as precursors to alkali-activated binders. Each precursor will need the correct activator (or combination of activators) to be identified, specified and sourced. There is currently little systematic or predictive information available regarding methodologies or heuristic

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procedures by which activators can be optimally matched to precursors, so this is currently achieved largely through parametric testing, but the need for improvements in this area has been identified [10].

Alkali-activated binders can be used in a wide variety of ways, in precasting as well as in situ concreting. It has often been stated that these materials are probably best suited to precasting or other situations where alkaline reagents can be appropriately handled and careful control of curing is possible [7, 11]. However, industrial-scale deployment of alkali-activation technology in some parts of the world, for example in Australia, has largely been based around use for in situ concreting work because this is the area in which applications have arisen, such as the 40,000 m^3 of slip-formed pavement used at the Brisbane West Wellcamp Airport in 2013-4 [12], as well as utilization in numerous road infrastructure projects by the state agency VicRoads [13, 14] and other end-users [15]. Longstanding application and standardization of these materials in Russia and Ukraine has been based on both pre-cast and in situ work [6, 16, 17], as have the deployment of ‘Pyrament’ in North America in the 1980s-90s [18-20], and recent larger-scale applications in South Africa [21, 22], the Netherlands [23] and the UK [24, 25]. Related materials and systems, using alternative forms of chemical (as opposed to strictly alkaline) activation and high-calcium fly ashes, have also been deployed commercially in the USA [26, 27]. Established concreting protocols and skill sets are largely applicable for the handling and placement or casting of concretes based on alkali-activated binders; workability of these materials in the fresh state can be more challenging than a modern Portland cement concrete due to the current unavailability of highly effective rheology control agents, but it has been demonstrated in the field that an experienced concreting workforce can use alkali-activated materials effectively.

Alkali-activation can sometimes be a relatively inexpensive option compared to the use of conventional Portland cement [9], particularly in locations which are relatively remote and thus require cement to be imported [28]. Although sourcing of activators can also be challenging in such regions, the volumes which must be transported are reduced by a factor of around 10 compared to importing of cement, which has been identified to offer advantages where an aluminosilicate raw material (e.g. coal fly ash or other industrial by-products, or a local volcanic or clay-based soil) can be sourced locally.

The discussion to follow will be focused on the potential for use of alkali-activation to produce both reinforced and non-reinforced elements with environmental benefit. The review of existing literature and industrial applications in a document such as this is by necessity less than exhaustive, and the reader is referred to the RILEM Technical Committee report edited by Provis & van Deventer [3] for detailed descriptions of the history and state of the art related to these materials.

2 Technology presentation

2.1 Description

Alkali activation is the generic term which is applied to the reaction of a solid aluminosilicate (termed the ‘precursor’) under alkaline conditions (induced by the ‘alkali activator’), to produce a hardened binder which is based on a combination of hydrous alkali-aluminosilicate and/or alkali-alkali earth-aluminosilicate phases. This definition may also appear to include high-volume blends of pozzolans or blast furnace slag with smaller quantities of Portland cement, but such cements are in general excluded from the definition of alkali-activation if the Portland cement is the main source of alkalinity.

Additional terminology which is often used regard to these materials can include 'geopolymer' nomenclature which is used largely (although rather indiscriminately) to describe low-calcium alkali-activated aluminosilicate binders, and discussion of 'hybrid binders' which include both Portland cement and a source of alkalis in addition to the main aluminosilicate component. These material systems generally fall within the broader domain of alkali-activation, and so will be included implicitly in the discussion below.

There are two main pathways by which alkali-activated binders can be produced, either a one-part mix (dry powder combined with water) or a two-part mix (liquid activator) system. The two-part mix type is probably the main pathway that will be followed in the initial deployment of alkali-activation in most markets, and the majority of the products that are already in the market are produced in this manner. However, it is likely that the one-part systems will become a more scaleable technology in the future due to the scope for factory production and distribution as a bagged material, once this technology becomes mature and various issues related to the often-slow strength development of one-part mixes are resolved. The two-part mixture appears more likely to be scaleable for precast work, where handling of chemicals and curing regimes can be more closely controlled.

As the solid precursor for production of alkali-activated materials, most common aluminosilicate supplementary cementitious materials are suitable for use, with blast furnace slag, coal fly ash, calcined clays and natural pozzolans having been demonstrated to give good results [3]. Blast furnace slags intended for use in alkali-activation require quenching (granulation or pelletization) and grinding to yield a reactive material. Other materials which are less commonly used in general Portland cement blends, but which have pozzolanic or hydraulic character such as Fe-rich clays [24], various slags from ferrous and non-ferrous metallurgy if air- or water-cooled to a reactive state and then finely ground [29, 30], clay-rich sludges resulting from water treatment [31] or kaolin purification [32], red mud [33-35], ground coal bottom ash [36], agricultural waste ashes [37], and fly ashes which do not meet the criteria specified in standards for use in Portland cement [38] are also of value in alkali-activation, although in the case of non-ferrous and steelmaking slags the leachability of toxic components must be considered with care. This may in fact prove to be a key avenue for the development of alkali-activated systems for niche applications, where there is not competition from Portland blended cements for the desired raw materials [2].

As alkali-activators, the most commonly used compounds used are MOH and $M_2O \cdot rSiO_2$, where M is either Na or K [39]. For activation of high-calcium precursors such as blast furnace slags, or for production of hybrid cements with a significant Portland cement content, Na_2CO_3 and Na_2SO_4 can also be effective [6, 10]. Some definitions of alkali-activation also include MgO, CaO and/or $Ca(OH)_2$ as potential activator compounds.

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The production of a one-part mix alkali-activated binder system has been demonstrated via co-calcination or intergrinding of various aluminosilicate powder precursors and solid activators, usually either an alkali carbonate, silicate or hydroxide [40-44]. Environmental benefits which may be obtained by such a processing route have also been highlighted [45].

In the on-site utilization of alkali-activated binders, and in factories in which they are used in pre-casting, it is generally important that appropriate personal protective equipment is used by the personnel. Specifically, protective equipment appropriate for handling of caustic alkalis is required in many instances. The alkaline activators can be classified either as corrosive or irritant depending on the activator selection, with an obvious practical and safety benefit gained from the use of materials which do not cross into the corrosive category [8]. The provisions for personal protective equipment which are specified in the Materials Safety Data Sheets for many commercially-available alkali-activated binder systems and concretes are actually very similar to those specified for the handling of fresh Portland cement paste and concrete; the importance of correctly following the required procedures is simply higher for alkali-activated systems.

The scope of application of alkali-activated binders is broad, and continues to grow, with demonstrated utilization in:

- Reinforced concrete
- Plain concrete
- Precast concrete components (including lightweight elements), both reinforced and unreinforced, and including pipes
- Mortars, grouts and renders
- Foamed and lightweight concretes
- Matrices for the immobilization of toxic and nuclear wastes, both organic and inorganic

2.2 Robustness of the technology

Is the technology suitable for:	Unknown	Proven Possible	Needs further development	Not possible
1) Use in poor and remote regions,		X (subject to activator availability; this will vary greatly between locations)		
2) Use by illiterate workers	X (will be some health and safety concerns			

	if suitable personal protective equipment is unavailable)			
3) Lack or poor control of aggregates,		X (evidence to date is that susceptibility to ASR is not excessive; reactive aggregate may actually be desirable in some instances [21]. Clay contamination in aggregate may cause issues in water content control)		
4) Poor control of water content,			X (robustness of performance, particularly in the fresh state, with regard to water content is challenging)	
5) Possible to use without admixtures		X (widely used without admixtures, because the majority of admixtures designed for Portland cement-based binders do not work effectively in AAMs)		
6) hot climates		X (higher temperatures, particularly with		

		high humidity, can be beneficial for curing. Hot, dry conditions require more careful control of curing to minimize water loss)		
7) Stability of workability at high temperatures			X (slump loss is a technical challenge for these materials in general; those mixes which set well under ambient conditions will tend to do so rather rapidly)	
8) High strength at early ages (precast)		X (well known and widely discussed that precasting is likely to be a highly advantageous route to market for AAMs, as it enables detailed control of both mix formulations and curing regimes)		
9) Sensitivity to common contamination		X (much more robust to some key contaminants, e.g. Zn, Cl or B, than Portland cement)	X (any parameters which influence the water/solids ratio in an uncontrolled way, e.g. clay in aggregates, will be problematic. Quality control of waste-derived or by-product raw materials is imperative, as there is no Portland	

			cement component to buffer intrinsic variability in sources of such materials)	

3 Durability of the technology

The durability of alkali-activated binders is addressed in detail in a recent RILEM State of the Art Report [3] as well as in published review papers [46, 47]. In general, chemical resistance of these cements (acidic or sulfate environments) is high, but there remain questions over carbonation and freeze-thaw resistance which are not yet fully understood [46, 48], and the value of some of the available information suffers due to limitations of standardized testing methods when applied to alkali-activated cements [49, 50]. Performance with respect to chloride ingress (diffusion or migration) appears in general to be comparable to that of materials based on Portland cement, but depends fundamentally on achieving a satisfactory microstructure in the binder through judicious mix design [51-53]. There are scattered reports of the in-service performance of alkali-activated concretes over extended timescales, but the data which have been released (which continue to increase in volume as these materials are deployed worldwide) tend to indicate satisfactory performance under a wide range of exposure conditions. There does exist some more detailed analytical information for slag-based binders dating from the 1950s-1970s [6, 54, 55], which indicates durability that was at least as good as that of Portland cement-based concretes poured simultaneously and serving under identical conditions.

Considering the elevated alkali contents of the majority of alkali-activated concretes, it may be expected that alkali-aggregate reactions could become problematic in these materials. However, this has not proven to be the case either in field or laboratory investigations [56-60]. Studies of efflorescence in alkali-activated binder systems [61-63] have generally concluded that the white 'bloom' which can appear on the surfaces of some alkali-activated mortars or concretes is usually related to the carbonation of mobile alkalis from the pore solution, and is best addressed through the implementation of curing conditions or addition of pore-refining additives (i.e. mineral admixtures rich in calcium and/or aluminium) to reduce the rate of moisture movement through the hardened cements. Control of efflorescence is, however, probably most straightforwardly achieved through a reduction in the dose of the alkali activator.

The very high alkalinity of alkali-activated binders seems to be favorable for protection of embedded reinforcing steel, and the use of these materials is well established in both reinforced and unreinforced applications.

4 Stage of development and research needs

Classify the stage of development of the technology

Innovation Phase	1) Conceptual phase	
	2) Laboratory evidence	
	a) Unanimous	X

		(very widely proven and demonstrated at laboratory scale
	b) Some debate	
	c) Important debate on fundamental issues	
Demonstration	3) Pilot plant	X (pilot or industrial scale demonstrations on every continent)
Public Policy	4) Standardization	
	a) 1 country	
	b) Some countries	X (Specific standards include UK: BSI PAS 8820:2016 performance-based specification for alkali-activated cementitious materials and concretes; Ukraine: extensive set of prescriptive specifications e.g. DSTU B.V. 2.7–181 (2009), Alkaline cements specifications; China: GB/T 29423-2012 corrosion-resistant specialty products; Switzerland: SIA Merkblatt 2049:2014, includes alkali-activated slag; Australia: state authority specifications e.g. VicRoads (Victoria) Section 703 for General Concrete Paving, Sections 701 &705 for drainage elements. Also within the scope of pure performance-based cement standards e.g. ASTM C1157, and performance-based product standards for precast blocks, pavers, tiles etc. in many jurisdictions)
	c) International	
Market Penetration	5) Commercial	
	a) one company, one site	
	b) one company, many countries	
	c) Few companies, several countries	X (Commercial-scale production and use in countries including: Australia, Brazil, Canada, China, Czech Republic, India, Netherlands, Russia, South Africa, Ukraine, United Kingdom, United States)
	d) widely known	

5 Potential of scalability

5.1 Raw materials

The main competitor for most of the aluminosilicate precursors used in production of alkali-activated binders is the use of the same materials in blends with Portland cement. The reserves and availability of those materials are thus generally limited by the same factors that influence their availability for Portland cement blends, and vary markedly between regions. Blast furnace slag and fly ash are produced in quantities totalling more than one billion tonnes per annum; in some regions (e.g. the United Kingdom) these are very limited in availability as the entirety of the quantity produced is consumed in Portland cement blends, while in other regions (e.g. India, China, Australia, South Africa) one of the other of these may be considered a waste requiring valorisation. The available resources of clays, lateritic and volcanic soils each exist in quantities vastly exceeding the likely global production of construction materials in the foreseeable future. Lateritic soils are predominantly (but not exclusively) found in tropical regions, which offers important possibilities for the use of this resource in alkali-activation in these areas which include some of the most important current and future markets for cementitious materials (India, Brazil, sub-Saharan Africa, and others). Volcanic resources are found in the Andean region, the Middle East, and in southern Europe (the original source of pozzolans), and clays are distributed more or less worldwide.

The fundamental source of alkali metals (particularly sodium) used in production of most alkali-activators is sodium chloride, obtained from seawater. This can be converted to sodium carbonate by the Solvay process (and thence to sodium silicate, or 'waterglass', via thermal or hydrothermal routes), or to sodium hydroxide by the chlor-alkali process. The co-products of these processes, $CaCl_2$ in the case of the Solvay process and Cl_2 from the chlor-alkali process, are themselves valuable commodity chemicals, although a very large expansion in their production accompanying major scale-up of alkali-activation technology may necessitate further thought around growth in their marketing and utilisation. Sodium carbonate can also be obtained as a geological resource, with 23 billion tonnes of proven resource of trona ore ($Na_3(CO_3)(HCO_3)\cdot 2H_2O$) in the north-western USA, and multiple hundreds of millions in Botswana, Turkey, Mexico and elsewhere [64]. The total global production of sodium carbonate exceeds 50 million tonnes, just under half of which is from mineral sources with the balance obtained from the Solvay route. Sodium hydroxide from the chlor-alkali process is on a similar scale, around 60 Mt per annum. Alkali silicates are produced at around one tenth of this throughput, but do not require particularly exotic process technology or very high temperatures for production (e.g. by dissolution of natural sand into NaOH solution under hydrothermal conditions), and so are potentially a scaleable product.

Competing markets for these potential activators are largely in the manufacture of commodity chemicals (detergents, zeolites, adhesives) and in papermaking and glassmaking. Large-scale deployment of alkali-activation using silicate or hydroxide activators would need scaleup of waterglass production, and/or decoupling of NaOH from Cl_2 production (i.e. using an alternative to the chlor-alkali process), for large-scale deployment. Na_2CO_3 production is extremely scaleable in regions with natural mineral resources, and existing production capacity is underutilised by several million tonnes per annum at present [64].

6 Comparison with OPC

6.1 Production process

There does not appear to be a strong need to develop new process facilities in the short term to enable the production of alkali-activated concretes. Mixing and casting/placement of alkali-activated concretes can generally be achieved using the same technology as is used for Portland cement concretes, potentially with slight modifications to optimise the input of mixing energy and the dosing of the activator. Precursors and activators are produced and prepared using existing processes.

Rotary kilns are not necessarily required; clay calcination can be achieved by either rotary or flash processes, slags require grinding (which is usually achieved in a ball mill), and fly ash may need some minor beneficiation or drying depending on the duration and location of its storage prior to use. The capital costs of a plant producing alkali-activated materials will therefore be significantly lower than that of a plant producing Portland cement. An increase in the scale of waterglass or sodium hydroxide production to support million-tonne-scale production of alkali-activated binders will require more capital-intensive facilities, but the activator only comprises 5-10% of the total mass of the binder and so the throughputs of such facilities will be much lower than that of a conventional cement kiln, and electrical rather than fossil energy is generally used to drive these thermal processes due to the moderate temperatures used.

6.2 Materials processing and application

Mix design of alkali-activated concretes can broadly follow similar heuristics to those used for Portland cement concretes, particularly in terms of aggregate grading, but the binder must be designed and optimized on a case-by-case basis: the precursors available in each location will differ in chemistry, mineralogy and fineness, and will be combined with activators which are selected depending on both technical and commercial parameters. There is not yet a universal mix design procedure which can be applied to alkali-activated binders or concretes, due to the differences in chemistry, mineralogy and particle characteristics between different precursor sources (although various protocols have been published which apply to single sources of raw materials, usually fly ash, these are of limited transferability between materials), so optimization of mixes needs to be carried out for each new precursor (or blend thereof) that is sourced. Accurate quality monitoring and control of the characteristics of precursors which are sourced as wastes or by-products from other industries is also essential to the successful production of alkali-activated concretes or concrete products.

Setting times of alkali-activated materials are in general similar to those of Portland cement-based materials. Alkali-activated slag cements tend to harden rather rapidly, and in some cases retarders are used to regulate the setting rates [65, 66]. For fly ash-based materials, heat curing is often applied to accelerate hardening of laboratory mixes, but the need for this treatment depends on the mix design (particularly activator dose and water content), and the reactivity of the fly ash. Many fly ashes, particularly those containing moderate amounts of calcium, can readily be combined with activators to generate high strength at ambient temperature; materials employed in commercial practice in North America have been based on ashes with sufficient reactive calcium content that the chemical activator need not be highly caustic [26]. Clay-based mixes can also react rapidly at room temperature, although control of the water content in binders based on rotary-calcined clays can be challenging due to the high water demand of the precursor particles. In many cases, the most important aspect of the curing regime is that sealed curing is highly desirable [67]; curing immersed in water can leach the activator and restrict strength development, and curing under dry conditions can in some cases cause surface cracking. Steam curing in a factory production environment has been demonstrated for production of precast elements, and alkali activation appears to have potentially high value in this mode of application.

Probably the main challenge related to processing and application of alkali-activated materials in construction at presence is the difficulty associated with developing or sourcing effective admixtures for rheology control in these systems. Initial efforts have led to the development of organic compounds which offer some improvements in performance [68, 69], but far from the levels of rheology achieved by superplasticizers in Portland cement concretes. The need for more detailed characterization of the solution-solid interface in alkali-activated binders has been identified as the key to improving performance in this regard [70], but at present the control of workability (and thus also workability retention) relies on the ability to continuously manipulate and optimize mix designs to achieve desired results.

7 Investment and Cost of production

The cost of production of alkali-activated binders is in general a closely-held trade secret, and is fundamentally dependent on the degree of control of the materials supply chain which is held by the producer. If precursors such as fly ash and slag must be purchased at a price which is similar to the unit price of Portland cement, the added cost of the activator will make these materials relatively more expensive. However, if the solid precursors can be sourced (or, in the case of clays, calcined) locally and cost-effectively, and the activator doses are kept low, cost-competitive production of alkali-activated binders is undoubtedly possible, as has been demonstrated by the successful commercial operations which are selling these products in several countries worldwide, as detailed above.

8 Simplified environmental assessment

Figure 1 presents an illustration of the inputs (materials and processes) involved in the production of an alkali-activated concrete, which are relevant to the discussion of environmental assessment. In any given production situation, factors such as the mix design (determined by performance and cost requirements), the source and dose of the activator, the transport requirements for aggregates and precursors, and the energy mix used in production of all components (i.e. electricity from coal, hydroelectric, nuclear, etc.), must all be specified for each particular mix design, location and application. When comparing with Portland cement-based concretes, a comparable baseline for that particular location and application must also be specified. For these reasons, it is clearly impossible to provide a single value – or even a well-

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defined range of values – to globally describe the environmental savings which may be able to be achieved through the use of alkali-activated materials in place of conventional cements and concretes.

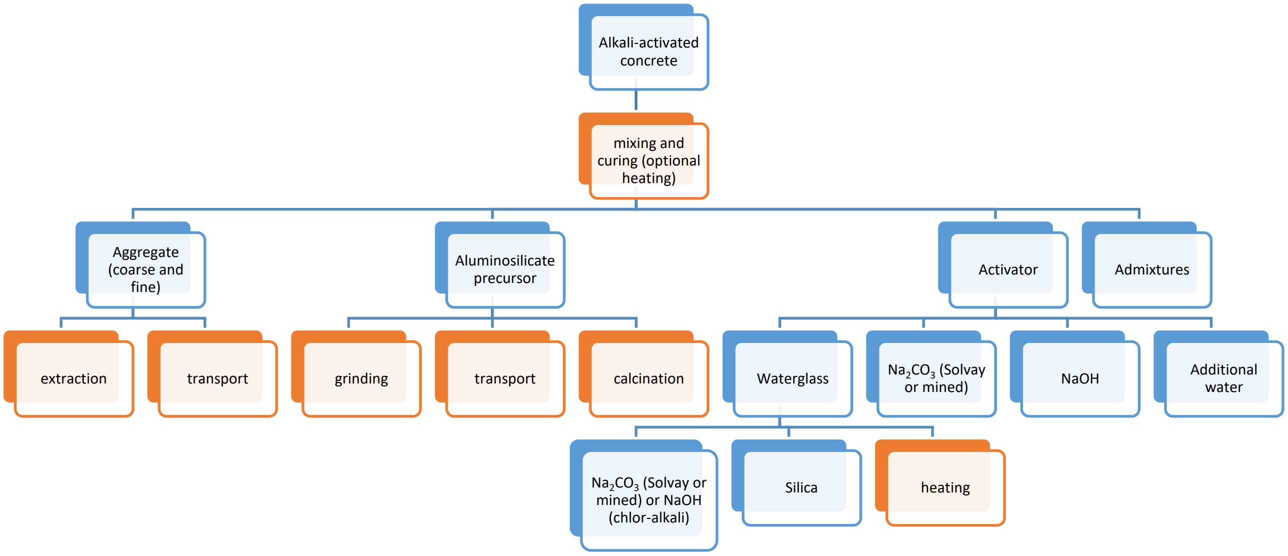

Figure 1. Depiction of the inputs which must be quantified, and assessed for emissions profiles, to conduct an environmental assessment of an alkali-activated concrete based on a two-part binder system. Materials are shown in blue, processes in orange, and all water added into the mix is considered to be a component of the activator for the sake of simplicity. Transport of pre-cast products after production is not depicted here but may also contribute to the overall environmental footprint; transport of activators and admixtures is considered a lesser contribution as the volumes/masses involved are generally much lower than those of the precursor and aggregate.

A detailed recent discussion of life-cycle analysis (LCA) of alkali-activated binder systems has been provided by Habert and Oullet-Plamondon [45], who examined in detail many of the recent discussions and debates around this still-contentious issue, and the reader is referred to that work for a much more comprehensive analysis than is presented here. Examples of LCA studies of alkali activation include [9, 45, 71-79], and these studies have resulted, in general, in calculations of between 40-80% CO_2 emissions reduction for the use of alkali-activated binders compared to a Portland cement baseline. However, the baselines are specified inconsistently between reports, and local conditions (including transport distances and electricity generation mix) as well as the choice of mix design for assessment will have important impacts on the results of the analysis.

The importance of reliable inventory data – which has not always been the case, particularly for activator components [45, 79] – and of attribution of emissions to by-product derived precursors [45, 72], has also been highlighted, but not fully addressed in the broader literature in this field. For a mortar based on blast furnace slag, activated by Na_2CO_3 and containing a high volume of granular limestone, CO_2 and energy savings as high as 97% have been calculated [80], while an inefficient mix design and an energy mix based on combustion of brown coal can lead to the calculation of savings of less than 10% compared to Portland cement [81]. In most cases, a realistic value will fall between these two extremes, but it is neither straightforward, nor likely to be correct, to narrow down this range any further in a generic sense.

The alkali activator will in the majority of cases be the dominant contributor to the environmental footprint of an alkali-activated binder, particularly where waterglass is used, as this can contribute as much as 90% of the total emissions footprint of many mix designs, and so must obviously be used judiciously in the design of an efficient alkali-activated material. A large number of published studies are based on a single source of data for the environmental footprint of a waterglass activator [82], which has become incorporated into international LCA databases. However, that study of the waterglass was based on data from industrial production in Europe in the 1990s, where the sodium carbonate used in waterglass production was sourced from the Solvay process (rather than the more efficient method of mineral extraction); there may also have been uncertainties in the method in which this was incorporated into widely-used databases, which have recently been updated to clarify this point [45]. Additionally, some extremely conservative assumptions were made regarding emissions of components such as chloride [79], which have carried through into product assessments for alkali-activated materials which thus appear to be much more environmentally damaging than Portland cement across various non-CO_2 emissions categories [45, 71]. This may or may not be the case in reality when database figures are updated to reflect modern waterglass production practices, and such calculations must be carried out in the future to provide a true assessment of the environmental footprint of alkali-activated binder systems.

For materials in service, the thermal insulation performance of a concrete based on alkali-activated binders is likely to be similar to that of a concrete of equivalent density based on Portland cement [83], although this is highly dependent on the moisture content of the materials [84], and so requires further detailed assessment both in the laboratory and in the field to determine relative saturation states as a function of ambient relative humidity and temperature. A wide variety of routes to foamed alkali-activated materials have also been demonstrated [85-91], and these offer pathways to the reduction of operational energy.

9 Barriers and incentives

The key barriers facing industrial-scale production of alkali-activated binders are largely outside the direct technical realm; these include the need for control of the supply chain, including reliance on alkali suppliers who have not historically been connected with applications in the construction industry, as well as competition for some precursor materials from existing uses in blended Portland cements. Key opportunities may therefore arise in areas in which this

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competition is less problematic, for example in Australia, South Africa and China with high levels of coal ash production, or via the use of calcined clays as is currently being undertaken in the United Kingdom. As mentioned in Section 2, occupational health and safety considerations may be significant for less-educated workforces. A proposed pathway from research and development through to implementation, deployment and acceptance is given in Figure 2 [92]; this is presented specifically for the case of alkali-activated cements but is likely to also have validity for other types of alternative cement in the more general sense.

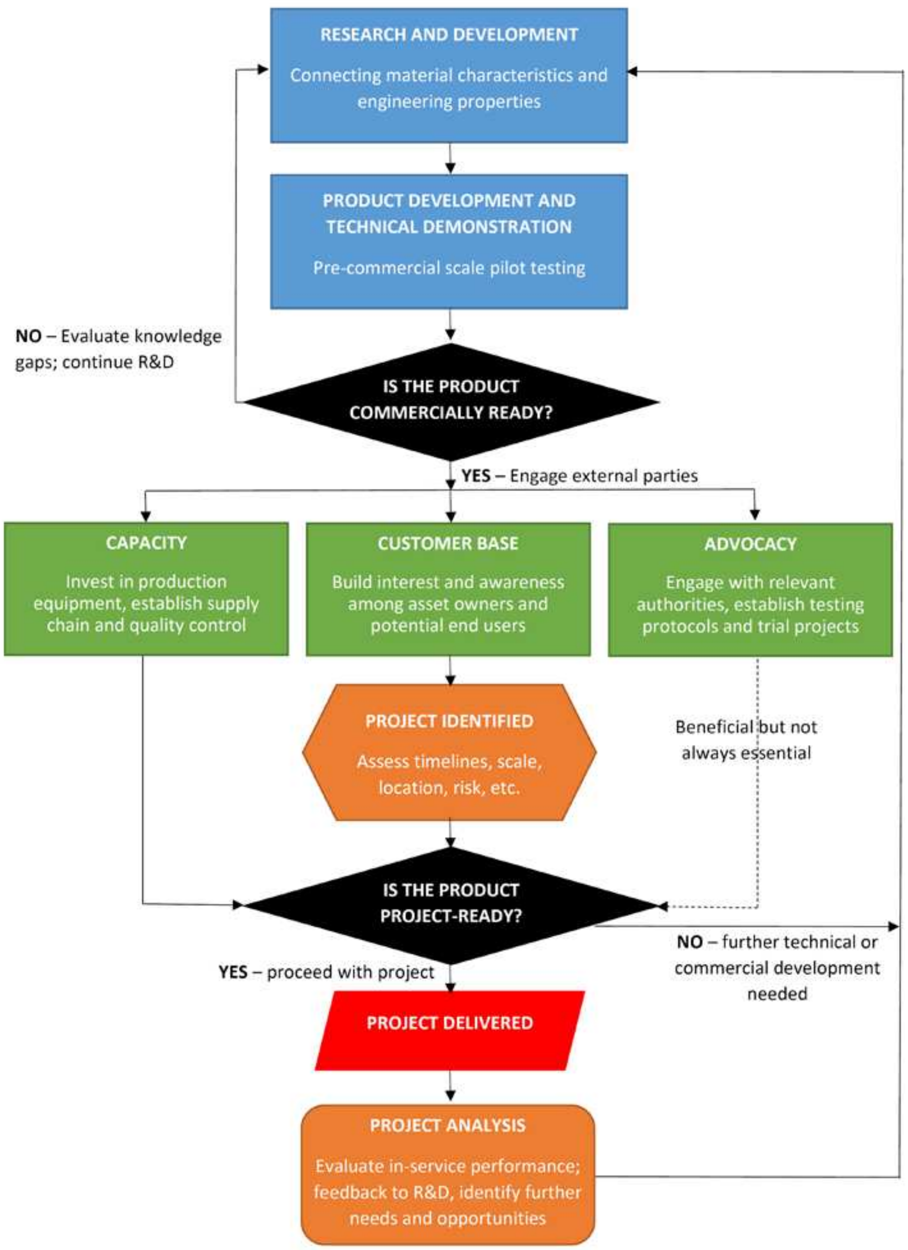

Figure 2. Conceptual illustration of the interconnected R&D and commercial advances which are required for field deployment of alkali-activated materials in construction. After [92].

Incentives for the uptake of alkali-activation technology include carbon emissions as discussed in section 8 above, as well as the valorization of natural resources, by-product or waste materials which are not currently used in an economic way. The high technical performance which can be achieved by alkali-activated materials, particularly in terms of resistance to chemical attack and to elevated temperatures [3], can also offer attractive possibilities in specialty applications such as sewer pipes [93, 94] or where fire resistance or refractory performance are desirable [95-97].

Standardization efforts related to alkali-activated materials are moving relatively rapidly (at least compared to the general pace of standards development in the construction materials industry) in several jurisdictions worldwide. In Switzerland, alkali-activated slags are explicitly incorporated into national guidelines [98], and in the UK, a Publicly Available Specification for alkali-activated cements and concretes has recently been published [99]. In the ASTM standardization regime, alkali-activated materials can be utilized under the performance-based standard C1157 [100], and further testing standards specific to these materials are currently under development. In China, the standard GB/T 29423-2012 [101] describes the use of alkali-activated materials for chemical resistance applications, and there is an extensive set of prescriptive standards for alkali-activated slag cements and concretes which has long been in place in Ukraine, Russia and other CIS nations derived from the work of the Glukhovsky Institute in Kiev [102]. In Australia, standardization has been driven bottom-up by specifiers rather than top-down by national regulators; the state roads authority of the state of Victoria (VicRoads) has updated four of their standard specifications to explicitly include alkali-activated concretes: Sections 703 (general concrete paving), 701 (drains and pipes), 705 (drainage pits), and 711 (safety barriers), with additional possible allowances for use of these materials under Section 610 (structural concrete) on a job-by-job basis [13].

10 Further research priorities

Research priorities in the area of alkali-activated materials include, but are not limited to:

- Development and optimization of mix designs based on an ever broader range of raw materials and activators, including both one-part and two-part binder systems
- Analysis of durability characteristics, in particular interactions between the binder and embedded steel reinforcing
- Development of appropriate admixtures to enable rheology control
- Development of activators with lower environmental impact than sodium hydroxide or sodium silicate, but with similarly desirable rapid early strength development
- Validation and standardization of testing methods and performance-based specifications directly applicable to alkali-activated cements and concretes
- Improved precision and technical basis of environmental assessment of activators, precursors and concrete mixes

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