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Applications

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Abstract Although alkali-activated materials (AAMs) show great promise as viable substitutes for Ordinary Portland Cement (OPC), they face numerous challenges in achieving widespread market acceptance. These challenges include the intricate chemistry of AAMs, technological and environmental complexities, inconsistency in the availability and quality of raw materials, and the absence of a well-established value chain for AAM production. Furthermore, legislative and regulatory frameworks are often lacking or unfavorable, and economic concerns related to scalability and competitiveness continue to pose barriers. Social acceptance remains limited, often due to unfamiliarity with the material and skepticism about its long-term performance. This chapter presents findings from various international research and development projects focused on advancing AAM technology. It highlights the pivotal role of pilot-scale trials in assessing the feasibility of AAM implementation, identifying technical and logistical challenges, and guiding further innovation. Additionally, the

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chapter showcases successful case studies and industrial applications of AAMs, positioning them as sustainable, high-performance alternatives to both traditional OPC and ceramic-based construction materials.

Keywords AAM applications · Pilot production · Building products · Case studies

1 Introduction

To date, alkali-activated materials have demonstrated their potential as alternative to Portland Cement (PC)-based concretes through many successful applications in the former Soviet Union and more recently in Western and Central Europe, Australia, China and North America, as described in the book [1]. However, as highlighted in the Chap. "Standardization and Legislation", their use is still limited as various barriers and obstacles prevent their faster market penetration. Pilot projects play a critical role in advancing this technology, as scaling up presents a multitude of complex issues to be solved. These challenges include:

- The complex chemistry influencing technical performance,
- Technological differences from PC, requiring multiple adjustments, especially in workplace safety,
- Environmental concerns including potential leaching issues,
- Consistency in performance due to the technology's reliance on variable waste materials,
- Availability of raw materials, many of which are either depleted or allocated for other uses,
- Incomplete value chains such as raw material logistics and grinding,
- Legislative and standardization challenges, including end-of-waste scenarios,
- Economic considerations such as the cost of activators and the final product price,
- Social acceptance and understanding.

The aim of this chapter is therefore to showcase some recent successful developments of alkali-activated products from research projects and recent industrial applications, providing evidence that such products can compete with existing PC or ceramic-based solutions.

Table 1 summarises some of the most famous examples of real-scale applications of alkali-activated concrete since their development to today [1].

Table 1 Examples of real-scale application of AAC

Year	Location	Project	Material
1952–1959	Brussels, Belgium	Parking 58	Purdocement (BFS + PC activated by $Ca(OH)_2$ or Na_2SO_4)
1960–1980	Mariupol, Ukraine	2-storey and 15-storey residential buildings	Alkali-hydroxide activated BFS concrete
1966	Odessa, Ukraine	Drainage collector No. 5	Alkali-carbonate activated BFS concrete
1974	Krakow, Poland	Storehouse	Precast steel-reinforced alkali-carbonate activated BFS concrete
1986–1994	Lipetsk, Russia	24-storey residential building	Alkali-carbonate activated BFS concrete
1988	Yinshan County, Hubei Province, P.R. China	6-storey office and retail building	Sodium sulfate-activated Portland-slag cement concrete
2009	Melbourne, Australia	Salmon St Bridge	E-Crete (Zeobond, AUS)—Precast footpath panel segments (180 precast footway units)
2009	Brisbane, Australia	Murrarie plant site bridge	EFC (Wagners, AUS)—Precast bridge decks
2010	Melbourne, Australia	Thomastown recreation and Aquatic Center	E-Crete (Zeobond, AUS)—Footpaths and driveways
2012	Melbourne, Australia	Melton Library	E-Crete (Zeobond, AUS) – Precast panels and in-situ works
2013	Queensland, Australia	Global Change Institute (GCI) Building, University of Queensland	EFC (Wagners, AUS) – 33 precast floor beam-slab elements
2013	Irvine, California, USA	Sustainable concrete solar-powered house	Precast alkali-activated fly ash concrete members
2013	Yuozhong District, Chongqing, P.R. China	Chongqing Research Institute of Construction Science office building	Cast in-situ alkali-activated BFS concrete
2014	Toowoomba, Australia	Toowoomba Wellcamp Airport	EFC (Wagners, AUS)—cast in-situ heavy-duty pavements
2018	Zeewolde, the Netherland	Cycle path	RAMAC (SQUAPE, NL)—Ready-mix cement-free concrete

(continued)

Table 1 (continued)

Year	Location	Project	Material
2020	Wageningen, the Netherland	Cycle bridge	RAMAC (SQUAPE, NL)—Ready-mix cement-free concrete
2021	Warsaw, Poland	P180 office building	Vertua® (CEMEX, UK)—Geopolymer clinker-free concrete
2021	Le Havre, France	Grand Port Maritime du Havre-concrete trail barrette	Exegy® (Soletanche Bachy, FRA)—GGBFS activated with sodium carbonate
2023	Mexico city, Mexico	The Sullivan 25 project—concrete foundations	Exegy® (Soletanche Bachy, FRA)—GGBFS activated with sodium carbonate

2 Case Studies from International Projects

Before introducing any new technology in standard practice, it is essential to conduct a thorough small-scale (pilot) verification. This preliminary phase aims to confirm the technology's feasibility and identify potential challenges. Small-scale testing allows for experimentation in real-world environments, which is crucial for accurately assessing the technology's performance beyond controlled laboratory conditions. This approach significantly reduces the risks associated with full-scale production and increases the likelihood of success. Furthermore, small-scale verification serves as a platform for iterative improvements. It enables developers to refine the technology based on actual performance data, ensuring that any modifications or optimizations are based on practical experience rather than solely on theoretical models. This step is particularly important in industries where safety, reliability, and efficiency are paramount, as is the case for the construction sector. Therefore, the small-scale verification is a critical step in the development and implementation of new technologies.

The following subsections present selected recent results from the small-scale production of alkali-activated materials (AAMs), which are summarised in Table 2.

Table 2 Small-scale demonstration projects based on AAM technology

Demonstration projects			
Project	Year	Materials	Products and applications
WOOL2LOOP	2019–2022	Geopolymer technology for the development of mineral wool waste value chains	Façade panels–Precast concrete walling sections
ERA MIN FLOW and ARRS J2-9197	2019	Alkali-activated concrete based on different binders (EAFS, LS FA, MK) and activators	FLOW insulating panels/blocks
Demonstration project in Rotterdarm (TUDelft)	2017	ECOCRETE (GGBFS + FA activated by calcium hydroxide + sodium carbonate + sodium sulphate	Reinforced alkali-activated concrete banch
URBCON	2023	GGBFS + calcium hydroxide + sodium carbonate	Reinforced precast pedestrian bridge
Semi-industrial examples			
Partek Oyj ABp (FIN)	1988	GGBFS + calcium hydroxide + sodium silicate	Roof tiles
NTPC NETRA + CSIR (IND)	2017	Alkali-activated FA	Concrete road
Leonardo d.o.o. + Nikotrans Begrad concrete plant (SLO)	2018	GGBFS + calcium hydroxide + sodium carbonate + sodium sulfate	Concrete floor slab (100 m^2)
Keko Geopolymers Ltd + Saint Gobain (FIN)	2020	GGBFS + sodium silicate + sodium hydroxide	Concrete floor slab (4 m^3)
Railway infrastructure project (London, UK)	2020–2021	GGBFS + PFA + activator A + activator B + activator C	Capping layer/piling platform (1400 m^3)
Jansen Beton	2021	SQUAPE geopolymer (GGBFS + FA + sodium hydroxide + sodium silicate)	Bycicle bridge
Hexham Flood Alleviation Scheme (UK)	2023	GGBFS + PC + activator	Flood defence wall

2.1 Façade Panels

WOOL2LOOP is an EU Horizon 2020 project started in 2019 and finished in 2022 [2]. The project attempted to solve one of the biggest challenges in the utilisation of waste mineral wool generated as construction waste during building and demolition processes. New smart demolition and sorting technologies were combined with a

Fig. 1 **a** Three shapes of panels (smooth, rough and wood imitation) and **b** the testing field at Termit d.d [3]. Foto archive of ZAG and Termit

novel analysis method for waste mineral wool in this project. After sorting, the mineral wool was pre-treated by milling to obtain a compacted material subsequently used in an alkali activation process. The mix design was developed and optimised for several concrete or ceramic-like materials and products such as acoustic panels, dry mix concrete, floor screed, pavement slabs, façade elements, 3D printing equipment for mineral wool AAMs, and fiber-reinforced panels were produced.

As part of the project, the Slovenian National Building and Civil Engineering Institute (ZAG) and the company Termit d.d. collaborated to develop an optimised mix design for the production of façade panels using waste stone wool and sodium silicate as an activator (TRL 6). The mixture consisted of waste stone wool, electric arc furnace slag, ladle slag, metakaolin, lime and quartz sand. The mixture was alkali-activated with sodium silicate made by Termit with M = 2.5. The binder consisted of 71.3 wt.% waste stone wool, 16.4 wt.% metakaolin, 10.2 wt.% of a mixture of electric arc furnace slag, and 2.1 wt.% lime, totalling 47 wt.%, while the sand accounted for 15.1 wt.% and the remainder sodium silicate. The water-binder ratio was 0.48.

The resulting alkali-activated façade panels, measuring 40.0 × 40.0 × 2.5 cm (smooth and rough panels) and 40.0 × 25.0 × 2.5 cm (imitation of wood) Fig. 1, were frost-resistant, successfully passing 150 cycles of freeze-thaw test. The panels were cured for three days at room temperature (in a closed bag) followed by three days at 60 °C and 60% humidity. The panels had bending and compressive strengths of respectively 14.9 MPa ± 3.2 MPa and 38.5 MPa ± 8.5 MPa. The open porosity of the prepared panels was about 20%, depending on the prepared batch. There was no bleeding, and the slump of the mix was measured at 165–170 mm [3].

2.2 Precast Concrete Walling Sections of Various Geometries

Another product demonstrated within the WOOL2LOOP project were precast concrete walling sections of various geometries (TRL 7–8 plant-level full-scale demonstration). This concrete was produced in 2022 in Veenoord, the Netherlands, by the Heembeton B.V, A CRH Company. GGBFS and mineral wool were used as the precursor and activated by sodium hydroxide and sodium silicate. The binder used in the mixtures consisted of 85 wt.% GGBFS and 15 wt.% mineral wool. The total binder content varied from 400 to 550 kg/m^3 of concrete during the demonstration. The aggregate skeleton was composed of sand 0–4 mm (588 kg/m^3), sand 0–1 mm (133 kg/m^3) and gravel 4–16 mm (578 kg/m^3). The development of mineral wool alkali-activated concrete for the production of precast elements followed a systematic step-by-step approach. In the first stage, a laboratory experimental program was conducted to create the mix designs with sufficient mechanical and durability properties. Upgrading the Heembeton factory (CRH precast factory in the Netherlands) with special tanks and piping systems for handling alkaline activators was the next stage. A complete safety audit of the production facility was conducted and necessary changes were made based on its findings to produce geopolymer concrete safely.

Several production trials were conducted at the plant using the finalized mix design to optimize the production process and to gain experience in industrial-scale production (Fig. 2).

Some performance requirements were identified for the precast alkali-activated concrete intended for walling sections. For example, slump flow spread diameter for self-compacting concrete should be ≥500–550 mm, the open time >20 min and the mixture should be cured under ambient temperature conditions to reach a one-day cubic compressive strength ≥20 MPa and 28 days cubic compressive strength ≥45 MPa. The final optimized concrete mixture showed a slump flow spread diameter of 500 mm, the compressive strength after one day was 34.0 MPa, 40.9 MPa after 7 days, 43.1 MPa after 28 days and 49.0 MPa after 56 days. No segregation or bleeding were observed. The concrete mixtures exhibited good fresh and hardened properties, however an increased cracking tendency was observed in comparison to the OPC concrete sections in the long term.

Fig. 2 **a** The pre-casting procedure and **b** the precast concrete walls. Foto archive of Arno Keulen

2.3 Steel-Reinforced Bench

In September 2017, a steel-reinforced bench (Fig. 3) was produced by the Microlab and concrete structure lab of the Delft University of Technology as part of a demonstration project in G.J. de Jonghweg Rotterdam, the Netherlands. GGBFS (ECOCEM, the Netherlands) and fly ash (FA) were alkali activated using calcium hydroxide, sodium carbonate and sodium sulphate as activators. The ECOcrete binder is composed of 50 wt.% GGBFS and 50 wt.% FA. To study whether the current design code fits the alkali-activated concrete design and demonstrate engineering applications, various properties of mixture were tested; e.g. slump was 25.5 mm and the initial setting time was 40 min [4]. The detailed composition of the mixture is stated in Table 3.

Fig. 3 **a** Preparation of the pre-casting model, **b** pouring the alkali activated concrete and **c** the final concrete bench [4]. Photo archive of TU Delft

Table 3 The composition of concrete mixtures

Components	Density (g/cm^3)	Mass (kg)*	Mass (kg)**
Fly ash	2.44	200	200
Blast furnace slag	2.89	200	200
Aggregate [0–4 mm]	2.64	789.14	789.14
Aggregate [4–8 mm]	2.65	439.81	439.81
Aggregate [8–16 mm]	2.65	524.69	524.69
Alkaline activator	1.125	200	212
($BaCl_2 \cdot 2H_2O$) admixture	3.1	–	2 (0.5 wt.% of the binder)

* Reference geopolymer concrete mixture [m^3]
** Optimized geopolymer concrete mixture [m^3]

2.4 Insulating Panels

In 2019, insulating (composite) blocks were produced in Slovenia by researchers from ZAG as part of the ERA MIN FLOW and ARRS J2-9197 projects. For the slag based porous blocks, dry mixtures of slag powders (grain size < 90 μm) with the electric arc furnace slag (EAFS)/ladle slag (LS) ratio = 1/1, FA and sometimes polypropylene fibers (Belmix, Mouscron, Belgium) with an average length of 11 mm were added. These were mixed with sodium water glass Crystal 0112 (Na_2SiO_2 containing 30.4 wt.% SiO_2, 15.4 wt.% Na_2O, and 54.2 wt.% H_2O, Tennants distribution, Ltd., Manchester, UK) and solid sodium hydroxide (Donau Chemie, Vienna, Austria). A second type of insulating blocks was based on FA (type F, obtained from a Slovenian thermal plant), metakaolin (MK) (Argeco), sodium silicate Crystal 0112 (Tennants distribution, Ltd.) and potassium silicate Betol K 5020 T (Woellner Austria GmbH). Sodium hydroxide and potassium hydroxide water solutions (both produced by Donau Chemie, 41.7 mass % water solutions) were used as activators. All cases used the foaming agents solid sodium perborate (Belinka Perkemija, Dol, Slovenia) or liquid H_2O_2 (Belinka Perkemija, Dol, Slovenia), and the stabilizing agent liquid Triton™ X-100 (Merck, Darmstadt, Germany). In the case of insulating composites, including lightweight aggregates (LWAs), expanded clay (Glinopor Vetisa d.o.o., Žalec, Slovenia), perlite (Njiva d.o.o., Žalec, Slovenia), expanded polystyrene (JUB, Dol, Slovenia) or expanded glass (Glasopor AS, Oslo, Norway) were used.

After laboratory optimization [5] for the production of larger panels, the two compositions designated P4 and P5 containing 66% slag (a combination of both slags EAFS and LS in a 1:1 ratio), 33% of activator and 1% foam stabilizer were chosen. The P4 composition was foamed using an additional 3.5 wt.% H_2O_2 whereas P5 was foamed with a combination of 5 wt.% H_2O_2 and 2.5 wt.% $NaBO_3$. Both panels were reinforced with 0.5 wt.% of PP fibers. The dimensions of the panels are 40 cm × 40 cm × 5 cm. The density of P4 is 0.5 g/cm^3, its flexural strength is 0.5 ± 0.2 MPa, its compressive strength is 1.5 ± 0.2 MPa and its thermal conductivity is 150 mW/m K. The P5 plate has the following properties: density 0.4 g/cm^3, flexural strength 0.7 ±

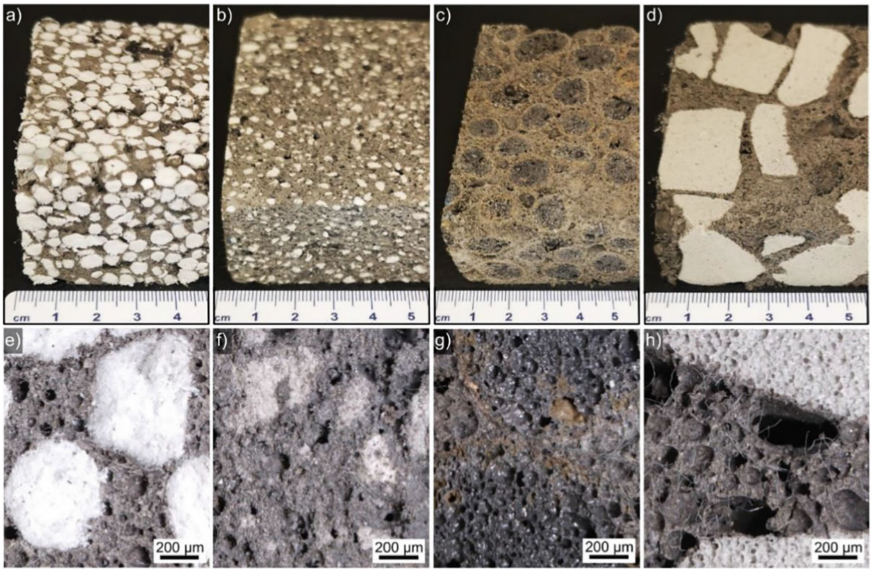

Fig. 4 Photographs of LWA–AAF composites containing. **a** EPS, **b** perlite, **c** EC, and **d** EG. Optical micrographs of cross sections prepared from the composites containing. **e** EPS, **f** perlite, **g** EC, and **h** EG reinforced by fibers are presented above [8]

0.2 MPa, compressive strength 1.7 ± 0.2 MPa and thermal conductivity 110 mW/m K [6]. Besides for thermal insulation at ambient temperature, inorganic alkali-activated foams (AAFs) can be used for high temperature insulations [7].

AAF composites incorporating LWAs can achieve superior mechanical properties when chemical bonding reactions or mechanical interlocking occurs during production. Chemical reactions are possible if the LWA contains an amorphous phase, which can react with the alkaline activators in the AAF, increase the bonding, and thus, also their mechanical strengths. These, in turn, allow for an improvement of the thermal insulation properties as they enable a further density reduction by incorporating low-density aggregates, and additionally LWAs counteract shrinkage of the matrix, providing the crack free samples presented in Fig. 4.

2.5 AAM Pavers

Between 2018 and 2019, floor pavers were produced by the KU Leuven as part of the KIC EIT Recover project. The paving tiles were produced by blending Koranel® with GGBFS in a 6:1 mass-ratio and activated with a potassium-based alkali silicate solution (SiO_2/K_2O molar ratio of 1.7 and water content of 65 wt.%). The liquid-to-solid ratio was approximately 0.4. The fresh mortars were cast into moulds (20 cm × 100 cm × 0.5 cm) and cured for a designated time at room temperature and 60%

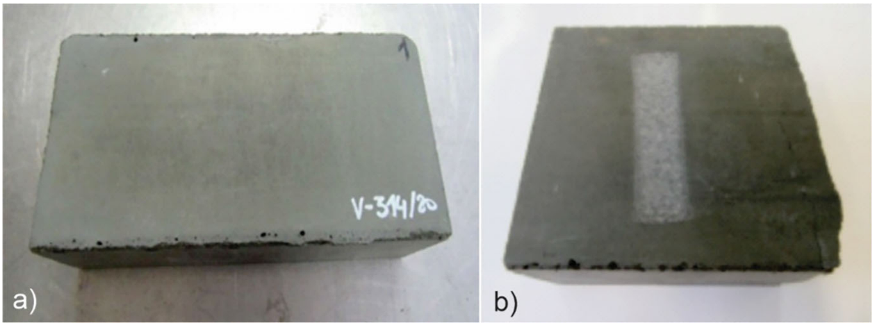

Fig. 5 **a** Recover paver and **b** paver after abrasion resistance test [9, 10]. Foto archive of ZAG

relative humidity (Fig. 5). The performance of the obtained pavers was compared to commercially available concrete paving blocks, and confirmed to be comparable, some properties such as the abrasion resistance and the freeze-thaw resistance in the presence of de-icing salt were even notably better [9, 10].

3 Semi-Industrial Examples

While the previous section presented products developed up to TRL levels of 6–8, this section describes cases in which the products are already being used in practice but have not yet been commercialized on a large scale.

3.1 Concrete Floor Slab of 100 m^2

In 2018, a commercial application in the form of a concrete floor slab (Fig. 6) of 100 m^2 (12.5 m × 8 m) in Kranj (Slovenia) was made by Leonardo d.o.o. (Slovenia) and the Nikotrans Begrad concrete plant (Slovenia). GGBFS (ECOCEM France SAS) was alkali activated using calcium hydroxide, sodium carbonate and sodium sulphate. The ECOcrete binder consisted of 85 wt.% GGBFS, 10 wt.% clinker and 5 wt.% kiln dust. The concrete mixture was composed of ECOcrete binder (360 kg/m^3), sand 0–4 mm (1030 kg/m^3), sand 4–8 mm (200 kg/m^3), gravel 8–16 mm (280 kg/m^3) and superplasticizer 0.7% (25% solid content). The water-to-binder ratio of mixture was 0.50. The alkali activated GGBFS mixture was pre-fabricated as a solid dry mixture with activators that hardened after adding water. Sodium carbonate and sodium sulphate were used as activators, with kiln dust partially replacing sodium sulphate. In order to speed up the reaction and achieve a rapid setting and hardening, calcium hydroxide or clinker were used as accelerators in the case of sodium carbonate activation. CEM I was added as an accelerator when sodium sulphate was used for activation. PCE

Fig. 6 Casting the concrete floor slab in Kranj (Slovenia) as a part of ECOncrete project [11, 12]. Foto archive of Zevnik lab

superplasticizers were ineffective in the sodium carbonate activation system, where sodium sulphate or kiln dust showed excellent behaviour. Some performance parameters were monitored for the industrial mixture, e.g. bleeding was not observed, the slump was 150 mm, setting times (initial and final) were 8.5 and 9.3 h and the air entrapment in the mixture was 1.9%. Compressive strengths were measured and the results are as follows: 4.0 MPa after 1 day, 13.5 MPa after 2 days, 30.5 MPa after 7 days, 42.0 MPa after 28 days, 43.0 MPa after 90 days and 65.0 MPa after 480 days. The on-site mixture also exhibited a excellent shrinkage behaviour and no corrosion or other damage has been detected so far [11].

3.2 *Concrete Floor Cast 4 m^3*

Another industrial-scale pilot is a 4 m^3 of concrete floor cast made in 2020 by Keko Geopolymers Ltd. and Saint-Gobain Finland in Lohja (Finland). GGBFS was alkali activated using sodium silicate and sodium hydroxide solution with GGBFS serving as the binder. The aggregates used were regenerated foundry sand, natural sand, and crushed granite with size fractions of 0–0.5, 0.5–1, 1–3, and 3–10 mm. Dry precursors and the activator solution were loaded into a concrete mixing truck, mixed and then delivered to the casting site. The workability of the mixture remained good for at least 3 h, allowing traditional concrete levelling and surface finishing techniques to be successfully applied. The mixture hardened within 12 h, so that it could handle people walking across the surface. To date, no corrosion or other damage has been observed (Fig. 7).

Fig. 7 **a** Casting the concrete and **b** vibrating the concrete to reduce air entrapment. Foto archive of Tero Luukkonen

3.3 Capping Layer or Piling Platform—Unreinforced

An unreinforced capping layer or piling platform, of approximately 1400 m^3 was made in London (UK) between 2020 and 2021 as a major railway infrastructure project. Alkali activated GGBFS and pulverised fly ash (PFA) was termed to be a "Geopolymer" and no further data was disclosed by the manufacturer (contracted concrete supplier—offsite). However, the concrete mix used for the application was composed of activator A (16.6 kg/m^3), activator B (16.6 kg/m^3), activator C (3.7 kg/m^3), GGBFS (285 kg/m^3), PFA (95 kg/m^3), sand 0–4 mm (762 kg/m^3), limestone 4–20 mm (1009 kg/m^3) and a superplasticizer (3.7 lt/m^3) with a water-to-binder ratio of 0.43. Another mix design consisted of activator A (16.6 kg/m^3), activator B (16.6 kg/m^3), activator C (3.7 kg/m^3), GGBFS (277.5 kg/m^3), PFA (92.5 kg/m^3), sand 0–4 mm (762 kg/m^3), gravel 4–20 mm (1009 kg/m^3), gravel 10 mm (303 kg/m^3) and a superplasticizer (3.7 l/m^3) with a water-to-binder ratio of 0.45.

The requirement for the project was for the capping layer of the piling mat to achieve a compressive strength of 15 MPa so that it could be used by the rigs for the project piling operations. A C32/40 with S4 slump class geopolymer mix was proposed for use on site after looking into the strength development of the mix and taking into consideration the project's programme. Two variations, one with gravel and the other with limestone, were developed based on availability of the aggregates at the batching plant. The gravel mix was mainly used. The initial batching plant trials showed an average compressive strength of 50 MPa 28 days after casting. Slump tests were carried out on every load as the product was placed and sets of cubes were taken for compressive strength tests. The averages of the compressive strengths were 8.4 MPa after 1 day, 12.4 MPa after 2 days, 22.9 MPa after 4 days, 27.6 MPa after 5 days, 35.2 MPa after 7 days, 46.9 MPa after 28 days and 51.7 MPa after 56 days (a total of 256 samples were tested).

The material was placed on-site using a pump and a skip, then vibrated. Even though the mixture appearing 'sticky', it pumped efficiently and flowed as expected for an S4 concrete mix. Curing such mixtures must be taken into consideration, as they need to be protected from even light rain, and water-based curing agents should

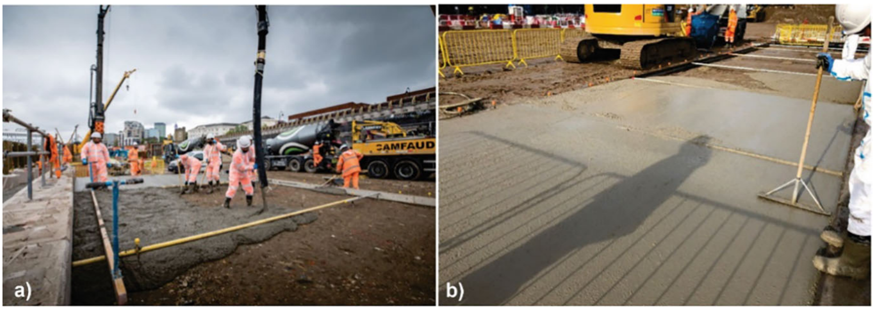

Fig. 8 **a** Placing the product using a pump, **b** finishing the surface. Foto archive of Dr. Kanavaris

not be used when finishing the surface. The final product shows a distinct green colour when cured properly, which gradually fades with exposure to UV light (Fig. 8).

3.4 Piling Guide Wall Construction and Unreinforced Capping Layer of Piling Platform (Fig. 9) (Volume 250 m^3)

A civil engineering project in the form of constructing a piling guide wall and the unreinforced top layer of a piling platform (approx. 250 m^3) was executed in London (UK) in 2020–2021. The concrete mix "Option 1-S4 consistence class" used for the application was composed of an activator (112 kg/m^3), GGBFS (338 kg/m^3), gravel marine 10–20 mm (630 kg/m^3), sand 0–4 mm (788 kg/m^3), gravel marine 4–10 mm (332 kg/m^3), superplasticizer (2.72 l/m^3) with a water-to-binder ratio of 0.39. "Option 2–200 mm target slump consistency" was composed of an activator and GGBFS (410 kg/m^3), limestone 10–20 mm (641 kg/m^3), sand 0–4 mm (842 kg/m^3), limestone 4–10 mm (395 kg/m^3), superplasticizer (3.00 l/m^3) with a water-to-binder ratio 0.38.

The requirement for the project was for the capping layer of the piling mat to achieve 15 MPa before it can be used by the rigs used for the projects piling operations. Similar requirements were in place for the guide wall construction. The concrete producer and product manufacturer proposed the two alternatives noted above. The first option includes a mixture of the activator and the GGBFS at the batching plant (Option 1—GGBFS from the concrete producer) and the other (Option 2—GGBFS from the product manufacturer) is a pre-blended powder (GGBFS and activator) which come into the batching process together. The specific product can provide a compressive strength class of a C28/35 mix with its compliance tested at 56 days. A mix with a consistence class of S3 was developed for the guide walls, after trailing a S4 mix, while a S4 consistence class mix was used for the piling mat to assist with on-site operations. The concrete mix was deposited on site using a concrete truck's

Fig. 9 **a** Depositing the product via the concrete truck's chute and **b** the finished product. Foto archive of Dr. Kanavaris

chute and was poured and vibrated just like PC. Consistency tests were carried out for every truck load, with all concrete batches complying with the required class. Sets of 100 mm cubes were taken during pouring. The averages of the compressive strengths in MPa were measured; 1 day: 4.2 MPa, 2 days: 8.6 MPa, 3 days: 16.4 MPa, 4 days: 16.5 MPa, 5 days: 20.2 MPa, 7 days: 24.8 MPa, 14 days: 28.2 MPa and 28 days: 34.0 MPa (altogether 26 samples). Option 1 was used based on logistics, availability, and difference in cost between the options.

3.5 Steel-Reinforced Precast Pedestrian Bridge in Rotterdam Bridge

In June 2023, a steel-reinforced precast pedestrian bridge was produced (Fig. 10) as a demonstration project within the URBCON project [13] in Rotterdam. GGBFS was alkali-activated using calcium hydroxide and sodium carbonate as activators, with 50% recycled aggregate replacing normal coarse aggregates in the concrete mix. The design strength class was C45/55, and the exposure classes were XD3 and XF4. To assess whether the current design codes are applicable to alkali-activated concrete and to demonstrate its engineering potential, various properties of the mixture, as well as the mechanical behavior of the elements, such as flexural and shear strength, were tested. The detailed composition of the mixture and the mechanical properties of the elements are provided in the URBCON handbook [13].

3.6 Bicycle Bridge

In June 2021, bicycle bridge [14] was built in Netherlands (Dommelen, part of N69 state road of Province Noord Brabant) (Fig. 11) produced by Jansen Beton (Son)

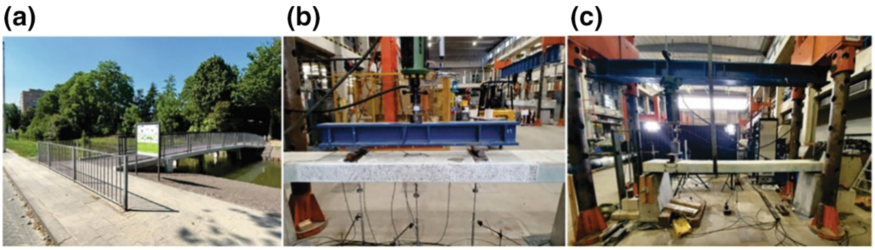

Fig. 10 **a** steel reinforced precast pedestrian bridge, **b** four-point bending test of reinforced beam element and **c** shear test of reinforced beam element [13]. Foto archive of Prof. Stijn Matthys

Fig. 11 Bicycle bridge in The Netherlands. Foto archive of Martin Verweij

with Sqape geopolymer technology under Boskalis Nederland contractor. GGBFS and FA were alkali-activated using sodium hydroxide and sodium silicate solution as activators using thermally recycled asphalt aggregates (fine and coarse aggregate) in the mix design. The design strength class was C33/43 (based on produced concrete) and with F4 pumpable consistency. The concrete surface of the structure was given a monolithic finish through trowelling to achieve a smooth, seamless appearance. In the construction of the bridge, prestress was applied in 2 steps, without bonding, to ensure optimal tension distribution and structural integrity.

3.7 Alkali-Activated GGBFS Roof Tiles

In 1988, Partek Oyj ABp in Parainen (Finland) performed pilot tests on an industrial scale with alkali activated GGBFS roof tiles. The tiles were installed on detached

Fig. 12 Alkali-activated slag roof tile [15]

house in Turku, Finland, where they were exposed to harsh Northern Scandinavian weather conditions for approximately 30 years. Few of the tiles were removed in 2019 and analysed for chemical and mineralogical composition, micro- and nanostructure, and carbonation depth as reported in [15]. The tiles were prepared with mix design containing 96 wt.% GGBFS and 4 wt.% calcium hydroxide was alkali-activated with a sodium silicate solution with a molar SiO_2/Na_2O ratio of 1. The binder content in the mixture was 280–460 kg/m^3 and the sand content was 330 kg/m^3. It was manufactured by co-grinding a dry mixture of 96 wt.% GGBFS and 4 wt.% calcium hydroxide. The mortar was then prepared by blending the aforementioned dry mixture with a sodium silicate solution (molar $SiO_2/Na_2O = 1$) in a weight ratio of 94:6, respectively, and adding 330 kg/m^3 of sand. The role of calcium hydroxide was to act as a setting accelerator. The GGBFS was from the Rautaruukki steel mill (Raahe, Finland). The Na_2O content in the mix design was 3–4 wt% of the GGBFS amount. The binder content was 280–460 kg/m^3. The roof tiles were prepared using an extrusion pressure process. The dimensions of the tile were approximately 430 mm × 330 mm × 25 mm (Fig. 12). Based on the analyses [15], it was concluded that roof tile had maintained excellent durability properties with little sign of structural disintegration in real-life living lab conditions, and thus provide in part assurance that AAM-based binders can be safely adopted in harsh climates.

3.8 Flood Defence Wall

In 2023, Tarmac (Hexham, United Kingdom) performed civil engineering project Hexham Flood Alleviation Scheme (Fig. 13) using alkali-activated GGBFS. The alkali activated concrete belonged to S4 consistence class and was composed of alkali

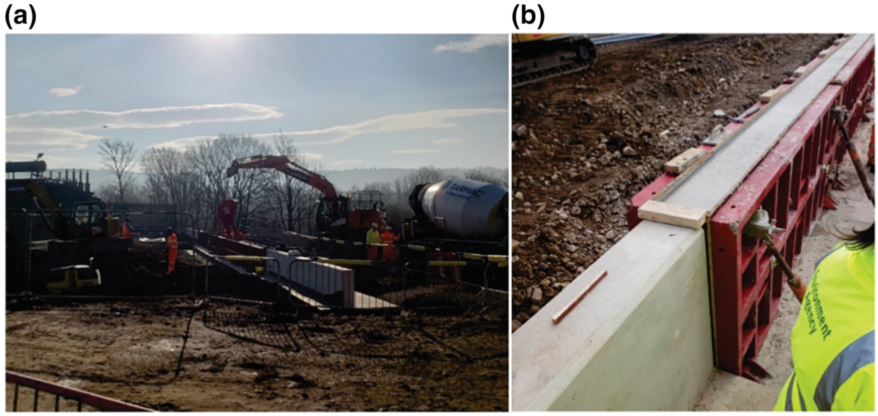

Fig. 13 **a** Placing the product via a concrete skip and **b** Finished product (in the formwork) [16]. Foto archive of Dr. Kanavaris

activator (36 kg/m^3, no further data disclosed by manufacturer), Portland cement (24 kg/m^3), GGBFS (438 kg/m^3), coarse aggregate 4–20 mm (820 kg/m^3), fine aggregate 0–4 mm (790 kg/m^3), plasticizer (5.3 kg/m^3), retarder (4.6 kg/m^3) and water (234 lt/m^3) with water-to-binder ratio 0.47 [16].

The requirement for the project was to trial a C32/40 concrete made from alkali activated concrete materials (AACMs) in a flood defence wall application. The concrete producer (Tarmac) proposed the mix including GGBFS as the main precursor with small amounts of Portland cement and an alkali activator. The binder was blended at Tarmac's Thrislington Concrete Plant. The specific product can provide a compressive strength class of a C32/40 mix. The mix was used in both the base and stem of the flood wall. The concrete was placed on site using a concrete skip mounted to a tracked excavator and was placed and vibrated as normal using a poker vibrator. Consistence testing was carried out using slump tests on every truckload. The average compressive strengths of the cubes taken from the material delivered to site were 13.4 MPa (1 day), 23.9 MPa (3 days), 33.5 MPa (7 days) and 43.4 MPa (28 days) (Fig. 13).

3.9 A Structural Application of Alkali-Activated Slag Concrete in Chongqing, China

In 2014–2015, alkali-activated slag concrete was used in a 23-story higher building in the Building of Chongqing Research Institute for Construction (Fig. 14). The first 7 stories were designed for laboratory and the stories above 7 were for offices. All beams, floors and columns were cast on-site using alkali-activated slag cement concrete from the 5th to 7th story. The total amount of alkali-activated slag cement concrete used was about 550 m^3, covering an area of 2000 m^2 [17].

Fig. 14 Alkali-activated slag demonstration project: **a** building; **b** construction section; **c** side view of the structure made with alkali-activated slag concrete [17]. Foto archive of Prof. Caijun Shi

The concrete mixture proportion design, structural design, and laboratory simulation were conducted by the research group at Chongqing University after extensive lab work. The structural design was according to Technique Specification for Application of Alkali-Activated Slag Concrete (DBJ50/T-205, 2014), and Code for Design of Concrete Structure (GB 50010). The concrete was mixed and cast on-site with requirements of initial slump of 220 mm $\pm$ 20 mm, slump loss should be $\leq$100 mm after 1 h, initial setting time of $\geq$6 h, final setting time of $\leq$12 h, and compressive strength grade of C50.

The concrete samples cured under standard conditions reached 58.4 MPa, while field samples reached 50.2 MPa at 28 days, with a standard error of 2.5 MPa for standard curing and 3.5 MPa for field curing samples. The building was completed in 2016. Inspection indicated that there were no surface defects, such as crusting and honeycomb, nor serious shrinkage cracking.

3.10 BFRP Reinforced Alkali-Activated Concrete Seawall Panels, Huilai County, China

The seawall of Xigang in Huilai County, Guangdong Province, was strengthened several times in recent decades due to the impact of waves and tidal effects. In the West Port seawall, 1.2 km of the new seawall is selected as the engineering application section of BFRP-reinforced alkali-activated concrete.

Table 4 Mix proportion of alkali-activated concrete in seawall test section

Sample ID	Strength grade	W/C	ρ	Binder	Sand	Coarse aggregate	Water
			(%)	(kg)	(kg)	(kg)	(kg)
GII-H-35	C35	0.4	42	440	720	1000	176

Fig. 15 Photos of the West Harbour seawall. Foto archive of Prof. Caijun Shi

Modified alkali-activated concrete (GII-H-35) with strength class C35 was used in the engineering application section. The binder material composition was slag: fly ash: silica fume: alkali activator: retarded component = 70:12:5:8:5, and the main alkali activators were solid sodium silicate (Ms = 1.4) and sodium carbonate. The mix proportion of concrete is shown in Table 4.

Alkali-activated concrete prepared by sea sand has good construction and mechanical properties and has been successfully applied in the construction of concrete panels of the sea wall of Huilai West Port with a length of about 1.2 km, and about 1800 m^3 of alkali-activated concrete has been poured. As shown in Fig. 15, the structure of the seawall panel is dense, and no cracks were found in the surface observation after 5 months. The compressive strength of the alkali-activated concrete sampled is 45.6–53.8 MPa.

4 Industrial Applications

Industrial applications are the final confirmation of a technology's suitability for broad and diverse use. When a technology is successfully applied in the industry, it provides clear evidence of several crucial aspects. Industrial application demonstrates the ability of a technology to function on a large scale, going beyond laboratory or pilot scale demonstrations. This is critical as many technologies face challenges in the transitioning from small, controlled environments to large-scale production in variable environments. For a technology to be viable in an industrial environment, it must not only function, but also increase the efficiency and productivity. This includes optimizing the use of resources, reducing downtime and improving the overall operational processes. The technical suitability is a basic prerequisite for the market launch of products, but economic viability is crucial in order to survive on the market. Some companies providing geopolymer technology are listed in Table 5, while selected industrial application cases are presented in Figs. 16, 17, 18, 19, 20 and 21.

5 Conclusions

Alkali activation is a rapidly emerging technology for low carbon solutions in construction. Although the development of alkali-activated materials dates back to the 1930s, significant advancements have made since, yet challenges remain. Numerous research projects are currently being conducted to validate this technology at a pilot scale. This chapter emphasizes the importance of small-scale verification in advancing this technology and presents several case studies to demonstrate its technical feasibility. Additionally, industrial applications are also presented as the ultimate test of a technology's suitability for a broad and diverse use. A successful industrial application demonstrates the scalability, efficiency, productivity and economic feasibility of a technology, all critical to a market success. Despite ongoing challenges, the numerous benefits and increasing applications of this technology indicate that alkali activation is becoming a key pillar in the transition from a linear to a circular economy in the construction sector.

Table 5 Industrial cases of geopolymer technology

Company name	Country	Technology product name	Main precursor	Main applications	References
Zeobond Pty. Ltd.	Australia	E-Crete™	FA, GGBFS	Pre-mixed concrete for driveways, footpaths, house-slabs, in-situ pours, wall panels and concrete pavers	[18]
Geopolymer Solutions LLC Corporate	USA	/	FA, GGBFS, steel production waste or naturally occurring minerals	Petrochemical industry, concrete for surface or subsurface mining, cellular concrete, structural concrete, spray-applied fire proofing and special applications requiring extremely low shrinkage and high chemical resistance	[19]
RENCA 3D Ink	Italy and Russia	/	Not reported	RENCA 3D Printing Geopolymer Mortar/Cement, Geopolymer Cement, Geopolymer Inorganic Resins and fire-protective, anti-corrosion and acid-resistant coatings	[20]
Wagners	Australia	Earth friendly concrete® (EFC)	FA, GGBFS	For infrastructure (airports, bridges, dams, rail, ports, marine), building and construction (multi story buildings, warehouses, houses), precast and concrete products (pipes, tunnel segments, bridges, blocks, and tiles) and proven applications (slabs, various permanent and temporary structural work, precast panels, tunnel segments, bridge girders, beams, pipes, plunge pools, and tanks, manufactured blocks, tiles, sleepers etc., shotcrete, block fill, footings, piling and custom builds)	[21–23]
Wortex	USA	GeoKrete® Structural Geopolymer and Geoliner® Geopolymer Mortar	Not reported	Geopolymer pipe lining	[24]

(continued)

Table 5 (continued)

Company name	Country	Technology product name	Main precursor	Main applications	References
Betolar	Finnland	Geoprime	Not reported	Pavers, slabs, curbstones and blocks in landscaping, concrete pipes, drain wells, drainage, manholes, box culverts, fence panels, noise barriers and retaining wall elements in infrastructure	[25]
Geobear	UK	/	Not reported	Subsidence solutions and treatment for ground	[26]
Gemite® Group	Canada	Corro-Chem™, Geo-Mortar™ or Geo-Cast™	Local FA or slag	Sewer rehabilitation, structural strengthening and other applications for such as chemical plants, surface protection and secondary containment, acid proof construction, mining—hydrometallurgy al processing, petrochemical processing, flue gas desulfurization and carbon capture, pulp and paper, acid resistant brick and tile, polymer concrete replacement, thermal insulation materials, manholes, culverts and tunnels, tanks for chemical liquids, fireproof systems and radioactive substances containment and encapsulation systems	[27]
Alchemy Geopolymer Solutions, LLC	USA	/	FA, GGBFS	Performance of experiments for power plants, construction industry, department of defense and federal government, sewer rehabilitation/repair industry, chemical plants, steel industry, coastal environmental protection, oil and gas industry, and building materials	[28]

(continued)

Table 5 (continued)

Company name	Country	Technology product name	Main precursor	Main applications	References
MC-Bauchemie Müller GmbH & Co. KG	Germany	/	FA, GGBFS	Products for concrete industry (admixtures and additives, concrete cosmetics, concrete goods, curing agents, grouts, release agents, waterproofing systems etc.), for engineering structures and industrial builds (systems for the sealing, protection and repair of commercial and residential buildings), and for building construction (protection and repair systems for engineering structures and industrial builds)	[29]
Sqape geopolymer technology	Netherlands	RAMAC	GGBFS, FA	RAMAC is the sustainable alternative to traditional road surfaces of concrete or asphalt. It can be used for cycle paths, roads and roundabouts	[30, 31]
Virtus Concrete Solutions Ltd.	UK	Blockwalls™	Not reported	Pre-cast geopolymer concrete blocks made from reclaimed stone, kiln ash, inert waste and sodium silicate sourced from recycled e-waste	[32]
CEMEX	UK	Vertua® Ultra	Geopolymer clinker-free concrete		[33]
Soletanche Bachy	France	Exegy	GGBFS activated with sodium carbonate		[34]
Geopolymer International	USA	GeoCement, GeoMortar, GeoPrint, GeoRockSpray	Not reported	General Purpose and assorted colour Geopolymer Concrete, Wood Fiber Geopolymer, Geopolymer 3D Structural Mortar, aerated and High Strength Geopolymer	[35]

Fig. 16 E-Crete™: **a** foothpath in park, **b** geopoymer drainage pipes, **c** precast panels to be fire-tested, **d** Structural panels at rear of Melton Library, **e** Tunnel segments and **f** housing development and **g** Melton Library & Learning Hub [18]

(a) (b)

Fig. 17 **a** RENCA 3D ink and **b** geocement and geosilicate [20]

(a) (b)

Fig. 18 Wagner Earth friendly concrete®: **a** Wet mix batch plant and **b** an aerial photograph of Brisbane West Wellcamp Airport [21]

Fig. 19 Gemite® Group: Sewer—Restoration & Waterproofing [27]

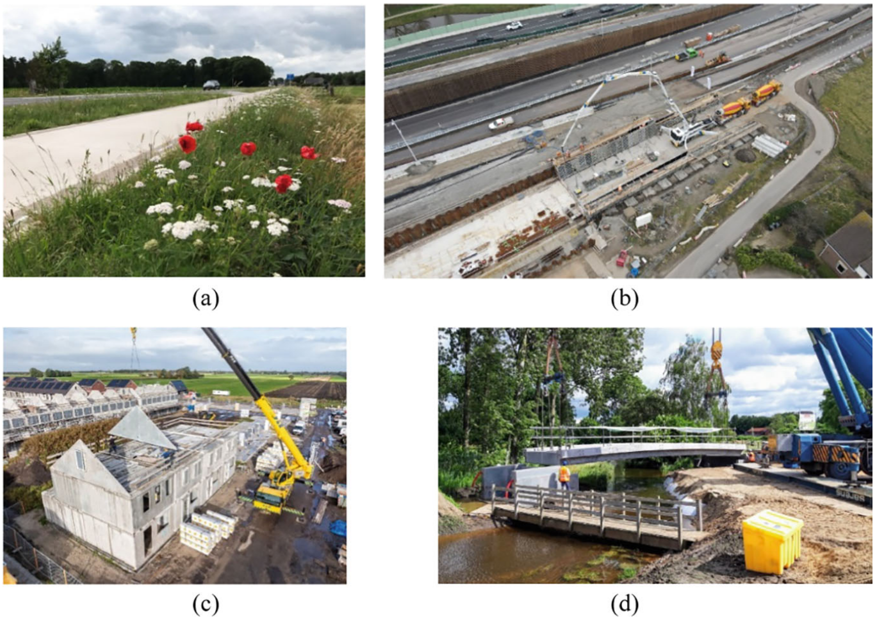

Fig. 20 **a** Rouwmaat Sqape geopolymer bicycle path, **b** Sqape geopolymer underpassage N206, **c** Heembeton Sqape geopolymer residential building and **d** Jansen Sqape geopolymer 100% recycled aggregates bridge N69 [31]

Fig. 21 **a** and **b** first 3D printed house out of geopolymers constructed in Amargosa Valley, Nevada in the spring of 2023 by Geopolymer International in collaboration with StrongPrint3D and Renca, **c** GeoBlock (MK-based) used for walls, as well as arches and domes, **d** GeoCement (MK-based) used for a variety of casting and spraying purposes including structural concrete, ornamental items, and repairs or fireproof coating [35]

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