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CHAPTER 9

Alkali-Activated Cement-Based Binders (AACB) as Durable and Cost-Competitive Low-CO$_2$ Binder Materials: Some Shortcomings That Need to be Addressed

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9.1 INTRODUCTION

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With an annual production of almost 3 Gt ordinary Portland cement (OPC) is the dominant binder of the construction industry [1]. The production of 1 t of OPC generates 0.55 t of chemical CO$_2$ and requires an additional 0.39 t of CO$_2$ in fuel emissions for baking and grinding, accounting for a total of 0.94 t of CO$_2$ [2]. Other authors [3] reported that the cement industry emitted in 2000, on average, 0.87 kg of CO$_2$ for every kilogram of cement produced. As a result the cement industry contributes about 7% of the total worldwide CO$_2$ emissions [4]. The projections for the global demand of Portland cement show that by 2056 it will double, reaching 6 Gt/year [5]. The urge to reduce carbon dioxide emissions and the fact that OPC structures that have been built a few decades ago are still facing disintegration problems points out the handicaps of OPC. Portland cement–based concrete presents a higher permeability that allows water and other aggressive media to enter, leading to carbonation and corrosion problems. The early deterioration of OPC reinforced concrete structures is a current phenomenon with significant consequences both in terms of the cost for the rehabilitation of these structures, and in terms of environmental impacts associated with these operations. Research works carried out so far in the development of alkali–activated cement-based binders (AACBs)

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showed that much has already been investigated and also that an environmentally friendly alternative to Portland cement is becoming more popular [6–8]. However, AACBs still show some shortcomings that need to be addressed so that they can effectively compete against Portland cement. For instance, Zheng et al. [9] mention some AACB problems, namely the difficulty of handling of caustic solutions, poor workability, quality control, and most important, the problem of efflorescences. Heidrich et al. [10] conducted an industry survey in Australia to identify the barriers to the adoption of AACB concrete, and conclude that the fact that this material is not covered by existent Australian standards or any other constitutes the main barrier. Strangely, only 30% of the respondents mention that the cost is a relevant barrier. However, it is important to mention that only 23.1% of the respondents had a detailed knowledge about AACB. The survey also pointed to the need for more research regarding AACB durability. This chapter thus reviews some AACB shortcomings, including its costs and carbon dioxide emissions, and also some durability issues like efflorescences, alkali silica reaction (ASR), and corrosion of steel reinforcement.

9.2 AACB COST EFFICIENCY

Currently the cost of AACB concretes is located midway between OPC concretes and high performance concretes [11,12]. These materials only start to become economically competitive compared to OPC concretes with a strength class above C50/60 [13]. Also the average ERMCO concrete class production lies between C25/30 and C30/37 and only around 13% of the concrete ready-mixed production is above the strength class C35/45 [14], which means that currently geopolymer binders are targeting a very small market share. For instance Pacheco-Torgal et al. [15–18] showed that tungsten waste–based AACB mortars can be more cost efficient than current commercial repair mortars. Therefore, in the short term the above-cited disadvantage means that the study of AACB applications should focus only on high-cost construction materials. The authors of Ref. [19] confirm that the high cost of AACB is one of the major factors that still remain a severe disadvantage over Portland cement. These authors suggest that waste-based activators could be used to overcome that gap. McLellan et al. [20] also suggests that the use of less expensive waste feedstocks may reduce AACB costs. Recently, some authors studied [21]. However, these authors did not provide any information regarding the costs of the new waste-based activator. Abdollahnejad et al. [22] recently studied foam fly ash–based two-part (NaOH, NaSiO$_3$) AACBs and reported that the mixtures cost more than 300 euro/m^3 (Fig. 9.1).
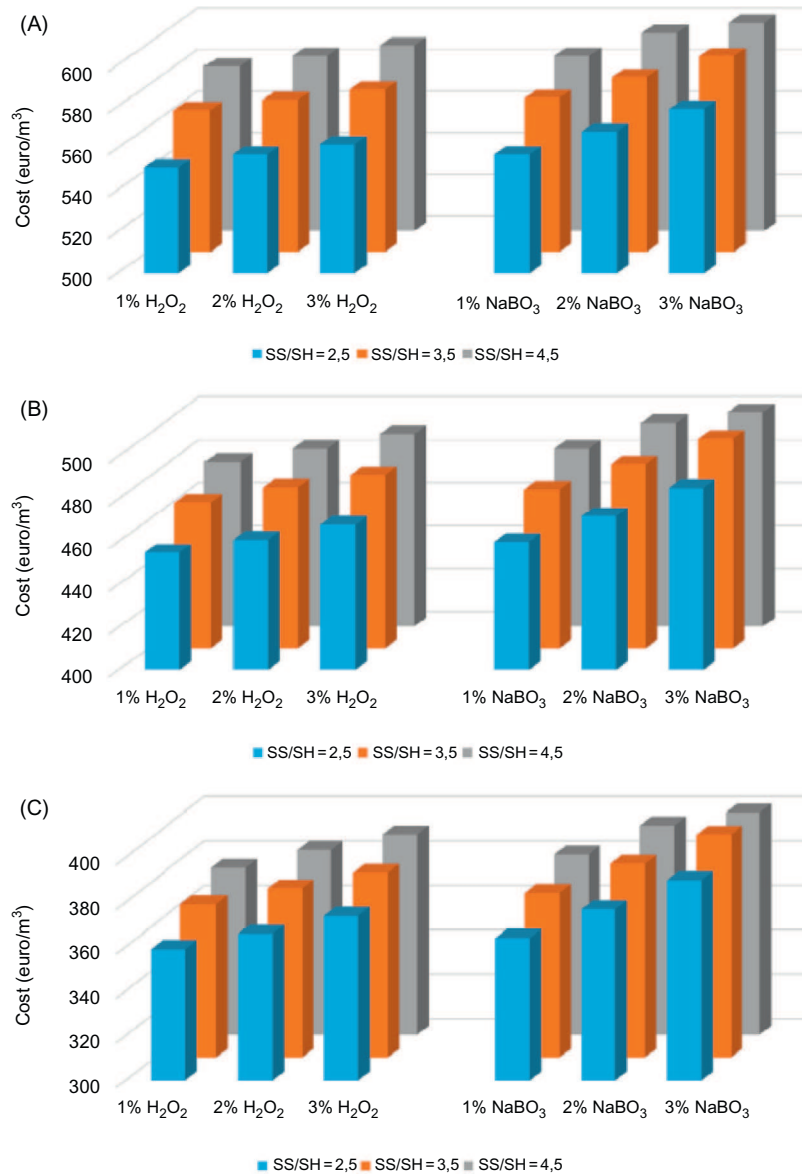
f0010   **Figure 9.1** Cost according to activator/binder ratio and sodium silicate/sodium hydroxide mass ratio: (A) activator/binder ratio =1, (B) activator/binder ratio =0.8, and (C) activator/binder ratio =0.6. *Reprinted from Abdollahnejad Z, Pacheco-Torgal F, Félix T, Tahri W, Aguiar A. Mix design, properties and cost analysis of fly ash-based geopolymer foam. Constr Build Mater 2015;80:18–30. Copyright © 2015, with permission from Elsevier.*

p0020   Cristelo et al. [23] compared the costs of $3880\,m^3$ of Portland cement and AACB mixtures for jet mix columns and mentioned that the former has an average cost of almost 90% of the latter. However, it is important to emphasize that comparisons should have been made for identical service life assessed by durability parameters. Also these authors made their comparisons against a high-cost Portland cement (type I 42,5 R) that is rarely used for this application. There is no doubt that if they used the less expensive Portland cement type IV/A (V) 32,5 R [24] the cost performance of AACB mixtures would be much less cost competitive. That is why Provis et al. [25] recognized that new activators that allow for cost-efficient AACBs constitute a key aspect that should be further investigated.

s0020   ## 9.3 CARBON DIOXIDE EMISSIONS OF AACB

p0025   Davidovits et al. [26] was the first author to address the carbon dioxide emissions of AACB stating that they generate just $0.184\,t$ of CO_2 per ton of binder. Duxson et al. [27] do not confirm these numbers; they stated that although the CO_2 emissions generated during the production of Na_2O are very high, still the production of alkali-activated binders is associated to a level of carbon dioxide emissions lower than the emissions generated in the production of OPC. According to those authors the reductions can go from 50% to 100%. Duxson and Van Deventer [28] mention a commercial life-cycle assessment (LCA) conducted by NetBalance Foundation on Zeobond's E-Crete geopolymer, which was compared to standard OPC blends available in Australia in 2007. The binder-to-binder comparison shows an 80% reduction of CO_2 emissions while the concrete-to-concrete comparisons show around 60% savings. Such conclusions allow the presentation of E-Crete as a very impressive performer against OPC concretes (Fig. 9.2).

p0030   A recent E-Crete geopolymer LCA study [29] used a 100% OPC concrete as the reference concrete although the construction industry uses concrete mixtures with partial replacement of Portland cement by pozzolanic additions. ERMCO [14] reports that the ready-mixed concrete industry in the United States and United Kingdom used 22% of cement additions while some countries like Israel and Portugal used respectively 26% and 28%. Also important is the fact that the study mentioned that a 40-MPa reference OPC concrete requires $440\,kg/m^3$ of Portland cement. However, a similar 40-MPa 28-day compressive strength could easily be achieved with a mixture of just 200-kg/m^3 Portland cement type II 42,5
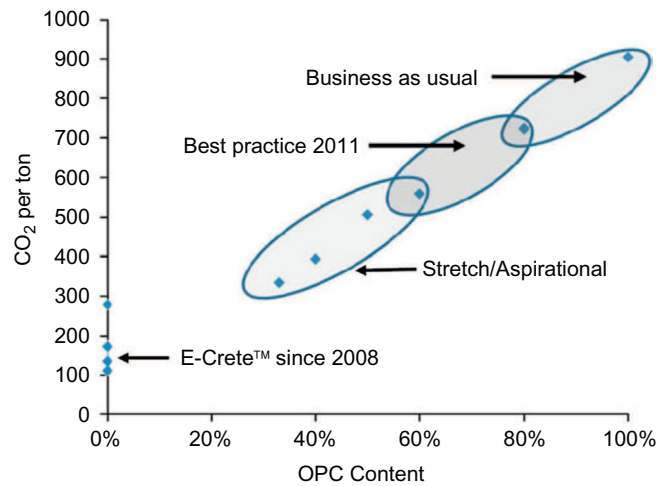
f0015   **Figure 9.2** CO_2 emissions of various cement binders as a function of OPC content. *Reprinted from Duxson P, Van Deventer JSJ. Geopolymers, structure, processing, properties and applications. In: Provis J, Van Deventer J, editors. Cambridge, UK: Woodhead Publishing Limited Abington Hall; 2009. Copyright © 2009, with permission from Elsevier.*

plus 300-kg/m^3 fly ash [30]. The LCA used an OPC with an emissions factor of 0.904 t CO_2e/t, which is very far from being the best OPC environmental performance. It also used an alkali activator with a 1.070 t CO_2e/t, which does not allow the assessment of which part is from the sodium hydroxide and which part is related to the sodium silicate. Weil et al. [31] confirm that the sodium hydroxide and the sodium silicate are responsible for the majority of CO_2 emissions in alkali-activated binders. These authors compared OPC concrete and AACB concrete with similar durability reporting that the latter has 70% lower CO_2 emissions. However, these authors' study used 100% OPC concrete and as it was previously mentioned this is not a mix solution used by the construction industry. Habert et al. [19] carry out a detailed environmental evaluation of alkali-activated binders using the LCA methodology, confirming that AACBs have a lower impact on global warming than OPC, but on the other hand, they have a higher environmental impact regarding other impact categories. McLellan et al. [20] reported a 44–64% reduction in greenhouse gas emissions of AACB when compared to OPC. Strangely, other authors [32] who also used Australian-based materials presented very different numbers. They showed that the CO_2 footprint of a 40-MPa AACB concrete was approximately just 9% less
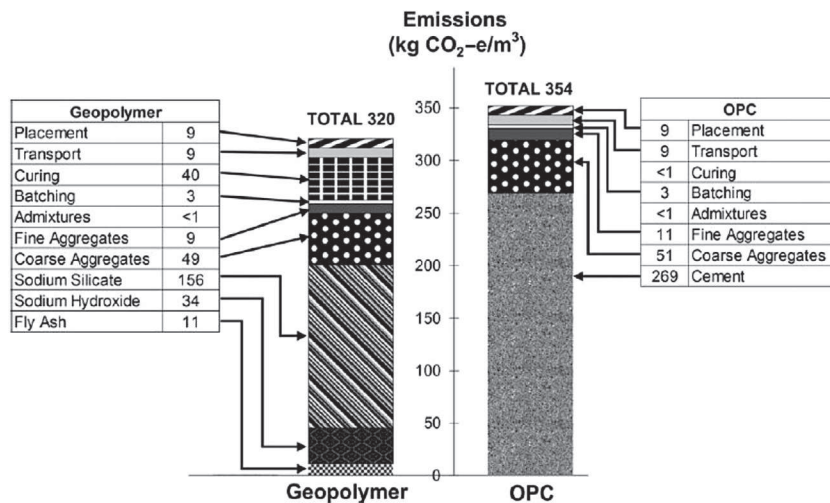
f0020   **Figure 9.3** Summary of CO_2-e for Grade 40 concrete mixtures with OPC and AACB. *Reprinted from Turner L, Collins F. Carbon dioxide equivalent (CO2-e) emissions: a comparison between geopolymer and OPC cement concrete. Constr Build Mater 2013;43:125–130. Copyright © 2013, with permission from Elsevier.*

than comparable concrete containing 100% OPC binder ($328 \, kg/m^3$). This is much less than the $440 \, kg/m^3$ used in the Aurora Construction Materials (ACM) [29] E-Crete LCA. The study of Turner and Collins [32] shows that the major part of geopolymer carbon dioxide footprints is due to sodium silicate (Fig. 9.3). However, it is important to remember (once more) that the construction industry does not use plain 100% OPC concretes; therefore, these mixtures should not be used as a reference comparison. The OPC concrete mixture used in this study could even have a much lower carbon footprint (below the AACB concrete carbon footprint) if fly ash had been used as partial replacement of OPC. A similar 40-MPa 28-day compressive strength could easily be achieved with a mixture of just $200 \, kg/m^3$ Portland cement [30]. These results confirm the fact that in some situations AACB can show "an emissions profile worse that of Portland cement-based concretes" as was already recognized by Ref. [7]. More recently, Provis et al. [25] emphasize that AACBs "are not intrinsically or fundamentally 'low-CO_2' unless designed effectively to achieve such performance."

p0035   Ouellet-Plamondon and Habert [33] confirmed that AACB only has better carbon dioxide emissions when comparisons are made against

100% OPC concrete–based mixtures. These authors mention that only one-part geopolymers show carbon footprint levels much lower than Portland cement, 10–30% when compared to 100% OPC mixtures. One-part geopolymers are considered an important phenomenon in the evolution of low-carbon AACB technology in the "just add water" concept. However, they were associated with low compressive strength [34]. The 2014 investigations of Peng et al. [35] confirm that one-part geopolymers show low mechanical strength. These authors noticed that one-part geopolymer mixtures show an increased reduced compressive strength after being immersed in water. This reduction is dependent on the kaolin thermal treatment. Higher calcination temperatures are responsible for higher compressive losses. Other authors [36] even reported a compressive strength decrease for one-part geopolymers based on calcined red mud and sodium hydroxide blends just after the first week of curing. Abdollahnejad et al. [37,38] investigated one-part geopolymers having obtained relevant compressive strength by using fly ash and minor amounts of OPC. Cristelo et al. [23] compared the carbon dioxide emissions of 3880 m^3 of Portland cement and geopolymer-based mixtures for jet-mix columns and mentioned that the AACB solution is responsible for just 77% of the Portland cement–based emissions. These results are only possible because these authors made their comparisons against a high-clinker Portland cement (type I 42,5 R). Also the emission factors that they used for sodium hydroxide and silicate (Table 9.1) are considerably lower than the ones used by Turner and Collins [32], respectively 1915 and 1514 kg CO$_2$eq/t. If they did use those emissions factors they would have to conclude that the AACB-based mixtures had a lower carbon dioxide footprint than the Portland cement–based ones. Strange as it may seem, Poowancum and Horpibulsuk [39] mentioned that AACB is a low-energy-consuming process and does not emit carbon dioxide. This shows the level of misunderstanding about these materials and that is related to the fact that, as it was previously mentioned, AACBs have been advertised as low-carbon footprint materials. However, since Davidovits [40] just mentioned that the carbon footprint calculations of sodium silicate in the paper of Habert et al. (2011) and in the paper of Turner and Collins [32] are wrong because these authors allegedly used the carbon emissions for 100% solid lumps, in place of the actual value of the diluted silicate solution (45% solid), which means that further studies are needed to confirm the real carbon footprint of AACB.

Table 9.1 Characterization of the activities involved in the production of 3880 m^3 of jet mixing columns

Activity	SC5A1			SA3a		
	Quant. (kg/m^3)	Emission factor (kg CO_2-eq/t) (database)	CO_2 (eq) (ton)	Quant. (kg/m^3)	Emission factor (kg CO_2-eq/t) (database)	CO_2 (eq) (ton)
Materials (prim.)[a]	—	—	836	—	—	630
Cement	200	930 (Sust. conc.)	720	—	—	—
Steel rebars	22	1351.47[b]	110	22	1351.47[b]	110
Fly ash	—	—	—	186	4 (Sust. conc.)	3
Water	100	0.3 (AEA, 2012)	0.1	100	0.3 (AEA, 2012)	0.1
Sodium hydroxide	—	—	—	50	999 (Ecoinvent)	194
Sodium silicate	—	—	—	75	1096 (Ecoinvent)	319
Energy (prim.)	—	—	53	—	—	53
Diesel	—	3.6028[c] (AEA, 2012)	49	—	3.6028[c] (AEA, 2012)	49
Network electricity	—	0.379285[d] (IEA—CO_2 emissions from fuel combustion)	4	—	0.379285[d] (IEA—CO_2 emissions from fuel combustion)	4
Mob/demob (second.)	—	—	17	—	—	13
Freight (second.)	—	—	54	—	—	44
People transp. (second.)	—	—	4	—	—	4
Assets (second.)	—	—	3	—	—	3
Waste (second.)	—	—	1	—	—	1

Source: Reprinted from Cristelo N, Miranda T, Oliveira D, Rosa I, Soares E, Coelho P, et al. Assessing the production of jet mix columns using alkali activated waste based on mechanical and financial performance and CO_2 (eq) emissions. J Clean Prod 2015;102:447–460. Copyright © 2015, with permission from Elsevier.
[a]Only the materials actively contributing to the CO_2 (eq) emissions are listed.
[b]The EF value used is a weighted average of the Ecoinvent v2.2 emission factor of the steel rebars (1857 kg CO_2-eq/t) and the recycled steel rebars (624 kg CO_2-eq/t), considering the 59% and 41% respective shares used.
[c]In this case the EF unit is kg CO_2-eq/L.
[d]In this case the EF unit is kg CO_2-eq/kWh.

9.4 SOME IMPORTANT DURABILITY ISSUES OF AACBS

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p0040   Duxon et al. [27] state that AACB durability is the most important issue in determining the success of these new materials. Other authors [41] mention that the fact that samples from the former Soviet Union that have been exposed to service conditions for in excess of 30 years show little degradation means that AACBs do therefore appear to stand the test of time. But since those samples were of the (Si +Ca) type that conclusion cannot be extended to geopolymers defined as "alkali aluminosilicate gel, with aluminium and silicon linked in a tetrahedral gel framework" [28]. Juenger et al. [1] argue that "[t]he key unsolved question in the development and application of alkali activation technology is the issue of durability." Also, Van Deventer et al. [8] recognized that "whether geopolymer concretes are durable remains the major obstacle to recognition in standards for structural concrete." Reed et al. [42] stated that the construction industry has not yet fully embraced AACB concrete mainly because the information pertaining to the service life and the durability of AACB concrete applications or infrastructure has yet to be quantified. Scrivener [43] also mentioned that the durability of AACB is not well known. The present section thus reviews three durability issues, namely, efflorescences, ASR, and corrosion of steel reinforcement.

9.4.1 Efflorescences

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p0045   Very few authors have investigated this serious limitation of AACB. Also a search on Scopus journal papers show that the first paper where this problem is mentioned was only published in 2007. Efflorescence is originated by the fact that "alkaline and/or soluble silicates that are added during processing cannot be totally consumed during geopolymerisation" [9]. It is the presence of water that weakens the bond of sodium in the aluminosilicate polymers, a behavior that is confirmed by the Rowles structure model (Fig. 9.4). In the crystalline zeolites the leaching of sodium is negligible, contrary to what happens in the aluminosilicate polymers [45,46]. Recently Skvara et al. [47] showed that Na, K is bounded only weakly in the nanostructure of the AACB (N, K)–A–S–H gel and is therefore almost completely leachable. This confirms that efflorescences are a worrying limitation of AACB when exposed to water or environments with RH above 30%.

p0050   Temuujin et al. [48] state that although ambient-cured fly ash AACB exhibited efflorescences, that phenomenon does not occur when the same AACB are cured at elevated temperature, which means the leachate
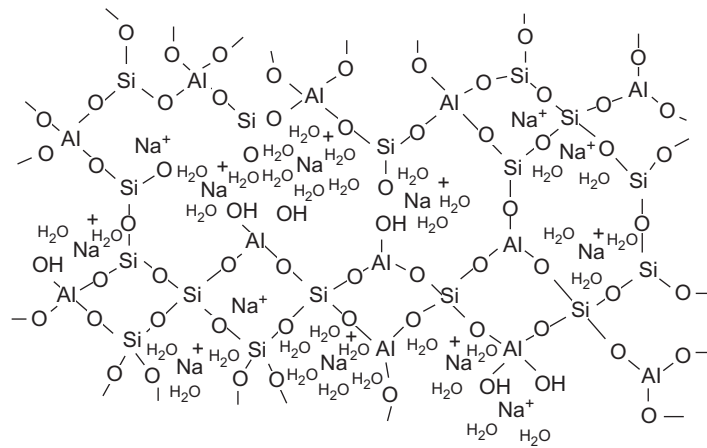
f0025   **Figure 9.4** Rowles structure model. *Reprinted from Rowles MR, Hanna JV, Pike KJ, Smith ME, O'Connor BH. 29Si, 27Al, 1H and 23Na MAS NMR study of the bonding character in aluminosilicate inorganic polymers. Appl Magn Reson 2007;32:663–89. Copyright © 2007, with permission from Springer.*

sodium could be a sign of insufficient reaction. Pacheco-Torgal and Jalali [49] found that sodium efflorescences are higher in AACB based on aluminosilicate prime materials calcined at a temperature range below the dehydroxylation temperature with the addition of sodium carbonate as a source of sodium cations (Fig. 9.5). Kani et al. [50] showed that efflorescences can be reduced either by the addition of alumina-rich admixtures or by hydrothermal curing at temperatures of 65°C or higher. These authors found that the use of 8% of calcium aluminate cement greatly reduces the mobility of alkalis, leading to minimal efflorescences. Zhang et al. [51] confirmed that hydrothermal curing can reduce efflorescence. They mentioned that NaOH-activated AACBs possess slower efflorescence than the sodium silicate solution–activated specimens.

p0055   According to Fig. 9.6 the lower Na-leaching rate is observed for the NaOH-based mixture (CL1H) while the higher one is related to the sodium silicate AACB (CL2H). Both were cured at 80°C for 90 days. A rather lower leaching behavior is associated with the AACB mixture CL1L made with NaOH and cured at 23°C having just 4.0 MPa at 90 days curing (Table 9.2).

p0060   A rather lower leaching behavior is associated to the mixture CL1L made with NaOH and cured at 23°C having just 4.0 MPa at 90 days curing (Table 9.2). A higher leaching behavior is noticed in the mixture CL2H that has a much higher compressive strength (58.4 MPa). These results are

f0030   **Figure 9.5** AACB mine-mortar specimens after water immersion. Above mortars based on plain mine-waste mud calcined at 950°C for 2 h. Below mortars based on mine-waste mud calcined at different temperatures with sodium carbonate. *Reprinted from Pacheco Torgal F, Jalali S. Influence of sodium carbonate addition on the thermal reactivity of tungsten mine waste mud based binders. Constr Build Mater 2010;24:56–60. Copyright © 2010, with permission from Elsevier.*

not in line with those of Allahverdi et al. [53] who mentioned that a highest compressive strength is associated with the least tendency for efflorescence formation. These authors also mentioned that slag-containing specimens showed much less and slower efflorescence. Still the role of calcium remains unclear and requires further study. The previous results seem to constitute a step back in the development of AACB. For one, AACBs based only on NaOH solutions without sodium silicate show moderate mechanical strength. Also, the use of hydrothermal curing has serious limitations for onsite concrete placement operations. On the other hand, the use of calcium-based mixtures reduces the acid resistance and raises the chances for the occurrence of the deleterious ASRs. Besides, the use of calcium reduces the global warming emissions advantage over Portland cement.
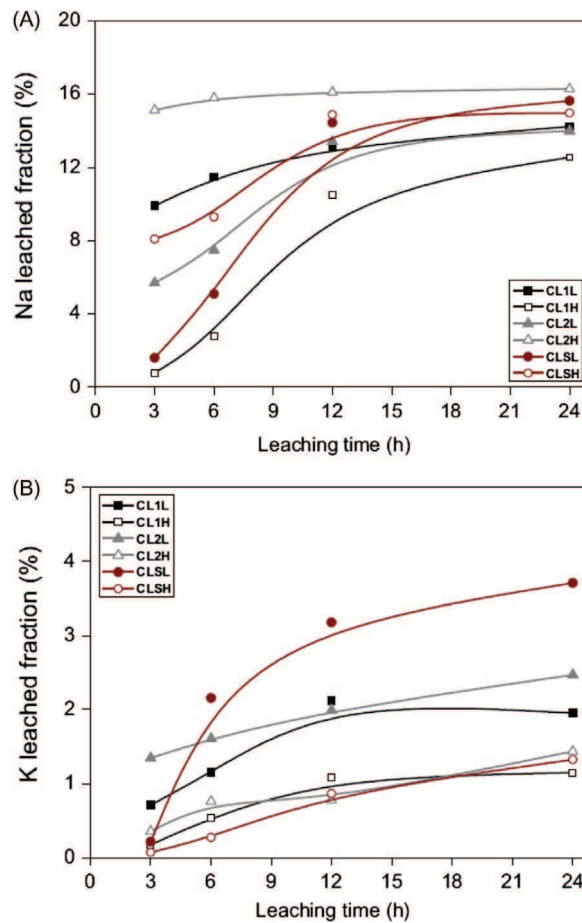
f0035   **Figure 9.6** The concentration of Na (A) and K (B) leached from the Callide fly ash mixtures. *Reprinted from Zhang Z, Provis J, Reid A, Wang H. Fly ash-based geopolymers: the relationship between composition, pore structure and efflorescence. Cem Concr Res 2014;64:30–41. Copyright © 2014, with permission from Elsevier.*

s0035   ## 9.4.2 ASR of AACBs

p0065   The chance that ASR may take place in AACBs is still a little-studied subject. For OPC binders, however, the knowledge of ASR has been intensively studied; therefore, some explanations could be also applied to understand the possibility of ASR when AACBs are used. ASR was reported for the first time by Stanton [54] and needs the simultaneous action of three elements in order to occur: (1) enough amorphous silica,

Table 9.2 Mix proportions and curing conditions of AACBs, and their compressive strengths at 90 days

Mixtures	Fly ash (g)	Slag (g)	Activator solutions (g)		Foam (g)	Curing scheme	Compressive strength (MPa)
	Callide		*12 M NaOH*	*$Na_2O \cdot 1.5SiO_2$*			
CL1L	100	0	23.1	0	0	23°C × 90 days	4.0 ± 0.3
CL1H	100	0	23.1	0	0	80°C × 90 days	26.2 ± 2.1
CL2L	100	0	0	35	0	23°C × 90 days	53.2 ± 0.9
CL2H	100	0	0	35	0	80°C × 90 days	58.4 ± 12.1
CLSL	80	20	0	35	0	23°C × 90 days	77.4 ± 7.0
CLSH	80	20	0	35	0	80°C × 90 days	58.2 ± 11.2

Source: Reprinted from Zhang Z, Provis J, Reid A, Wang H. Fly ash-based geopolymers: the relationship between composition, pore structure and efflorescence. Cem Concr Res 2014;64:30–41. Copyright © 2014, with permission from Elsevier.
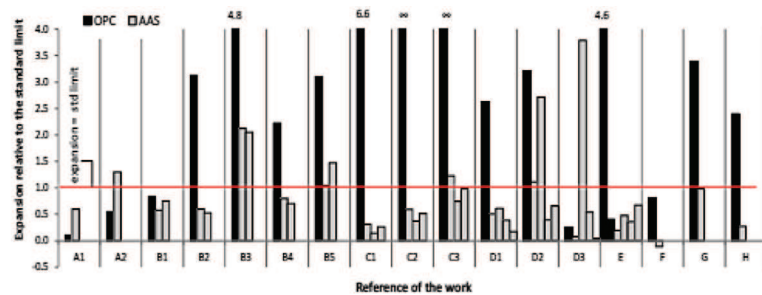
(2) alkaline ions, and (3) water [55]. The ASR begins when the reactive silica from the aggregates is attacked by the alkaline ions from cement, forming an alkali–silica gel, which attracts water and starts to expand. The gel expansion leads to internal cracking, which has been confirmed by others [56] reporting 4 MPa pressures. Those internal tensions are higher than OPC concrete tensile strength, thus leading to cracking. However, some authors believe that ASR is not just a reaction between alkaline ions and amorphous silica but also requires the presence of Ca^{2+} ions [57]. Davidovits [58] compared AACB and OPC when submitted to the ASTM C227 mortar-bar test, reporting a shrinkage behavior in the first case and an expansion for the OPC binder. Other authors [11,12] reported some expansion behavior for AACB although it was smaller than for OPC binders. However, Puertas [59] believed ASR could occur in slag-based AACB containing reactive opala aggregates. Bakharev et al. [60] compared the expansion of OPC and AACB, reporting that the former had higher expansion. This is clear from the microstructure analysis (Fig. 9.7).

p0070   Garcia–Lodeiro et al. [61] showed that fly ash–based AACB is less likely to generate expansion by ASR than OPC. They also showed that the calcium plays an essential role in the expansive nature of the gels. Investigations by Puertas and Palacios [62] show that siliceous aggregates are more prone to ASR than calcareous aggregates in AACB mixtures.
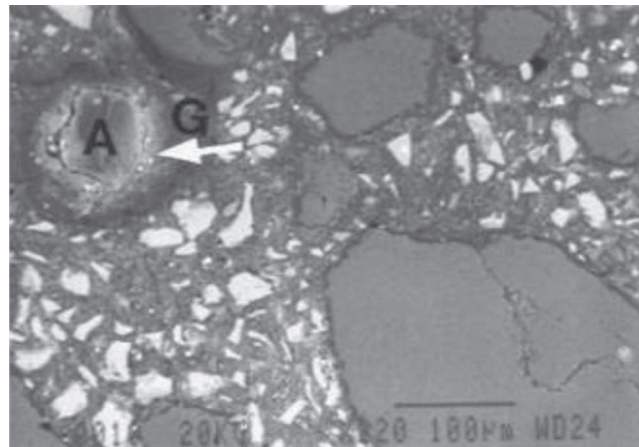
f0040   **Figure 9.7** AACB concrete after 10 months curing. Reactive aggregate; G = alkali–silica gel. *Reprinted from Bakharev T, Sanjayan JG, Cheng YB. Resistance of alkali-activated slag to alkali-aggregate reaction. Cem Concr Res 2001;31:331-4. Copyright © 2001, with permission from Elsevier.*

Cyr and Pouhet [63] reviewed the work of several authors concerning the expansion due to ASR (Fig. 9.8) noticing that some mixtures show an expansion above the limit proposed in the standard used for ASR tests. Therefore the study of ASR in AACB is not a closed subject, at least for the AACBs containing calcium.

	Reference	Temperature	Age of test	Explanation of the different AAS mixtures
A1, A2	Bakharev et al. (2001)	38°C	1 year	A1: nonreactive aggregate A2: reactive aggregate
B1 to B5	Gifford and Gillott (1996)	38°C	1 year	B1: nonreactive aggregate B2: reactive (ASR) aggregate S1 B3: reactive (ASR) aggregate S2 B4: reactive (ASR) aggregate V B5: reactive (ASR) aggregate B AAS activated with Na$_2$CO$_3$ or Na$_2$SiO$_3$
C1 to C3	Chen et al. (2002)	38°C	180 days	C1, C2 and C3: 2, 3.5, and 5% alkalis, respectively AAS activated with waterglass, NaOH, Na$_2$CO$_3$ or Na$_2$SO$_4$
D1 to D3	Metso (1982)	40°C	70 days	D1, D2 and D3: 3, 8, and 15% of opal, respectively Two types of slag, activated with 1.5 or 2.4% Na
E	Al-Otaibi (2007)	60°C	1 year	AAS activated with sodium silicate or sodium metasilicate, with Na$_2$O content of 4 or 6%% Two OPC references: doped and non-doped in alkalis
F	Fernandez-Jimenez A, Palomo A., Puertas F. (1999)	80°C	16 days	
G	Puertas et al. (2009)	80°C	14 days	
H	Wang et al. (2010)	80°C	14 days	

Figure 9.8 Ratios of the expansion relative to the limit proposed in the standard used for the ASR test, for Portland cement, and slag-based AACB mixtures. *Reprinted from Cyr M, Pouhet R. Resistance to alkali-aggregate reaction (AAR) of alkali-activated binders. In: Pacheco-Torgal F, Labrincha J, Palomo A, Leonelli C, Chindaprasirt P, editors. Handbook of alkali-activated cements, mortars and concretes. Cambridge, UK: WoddHead Publishing; 2014. p. 397–422. Copyright © 2014, with permission from Elsevier.*

9.4.3 Corrosion of Steel Reinforcement in AACBs

The corrosion of steel reinforcement is one of the causes that influences the structural capability of concrete elements. As concrete attack depends on its high volume and therefore is not of great concern, an attack on the steel reinforced bars is a serious threat eased by the fact that steel bars are very near to the concrete surface and are very corrosion sensitive. In OPC binders, steel bars are protected by a passivity layer, due to the high alkalinity of calcium hydroxide. The steel bars' corrosion may happen if pH decreases, thus destroying the passivity layer, due to carbonation phenomenon or chloride ingress. The steel corrosion occurs due to an electrochemical action, when metals of different nature are in electrical contact in the presence of water and oxygen. The process consists of the anodic dissolution of iron when the positively charged iron ions pass into the solution and the excess of negatively charged electrons goes to steel through the cathode, where they are absorbed by the electrolyte constituents to form hydroxyl ions. These in turn combine with the iron ions to form ferric hydroxide, which then converts to rust. The volume increase associated with the formation of the corrosion products will lead to cracking and spalling of the concrete cover. For AACB, the literature is scarce concerning its capability to prevent reinforced steel corrosion. Aperador et al. [64] mention that AACB slag concrete (AAS) is associated with poor carbonation resistance, a major cause for corrosion of steel reinforcement. The calculated carbonation rate coefficients were 139 and 25 mm (year)$^{-1/2}$ for AAS and OPC concretes. Fig. 9.9 shows the low corrosion resistance of AACB slag concretes. Other authors also confirmed the low carbonation resistance of AACB mixtures [65,66].

Lloyd et al. [67] showed that AACB is prone to alkali leaching, which could lead to a rapidly and disastrous reduction in the pH, causing steel corrosion. They stated that it is not certain how long a steel-reinforced AACB concrete structure would be able to resist corrosion. They also mention that the presence of calcium is crucial for having durable steel-reinforced AACB concrete because calcium-rich mixtures have much lower diffusion coefficients and a more tortuous pore system that hinders the movements of ions through the paste. Law et al. [68] recently recognized that for chloride-induced attack the long-term protection provided by AACB concrete may be lower than for OPC and blended cement concretes. It is true that as Criado [69] recommends, the use of stainless steel reinforcement could overcome the corrosion problems of AACB concrete;
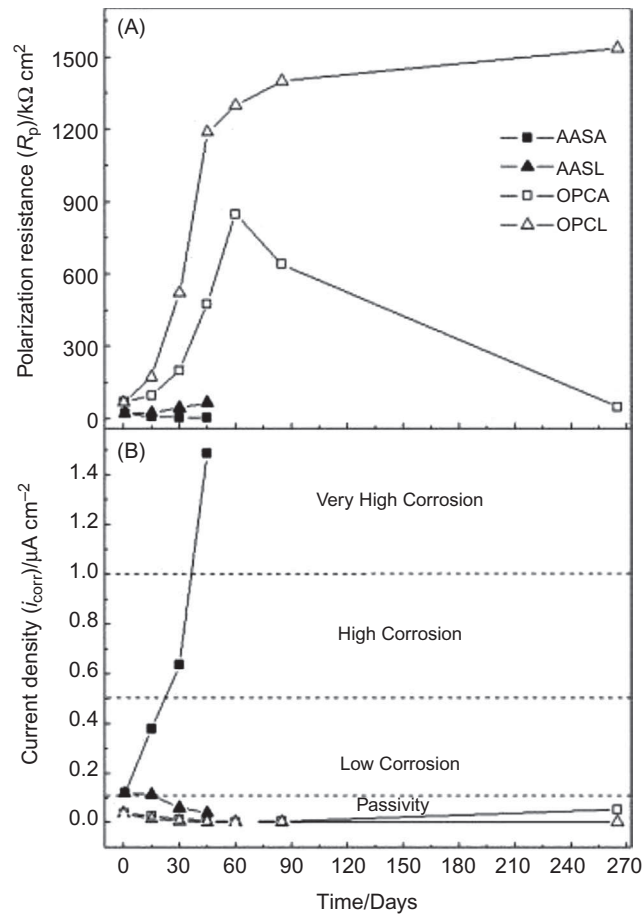
Figure 9.9 Polarization resistance (R_p) and current density (i_{corr}) versus time for steel rebars embedded in AAS and OPC concretes with and without exposure to carbonation: AASA and OPCA were exposed to accelerated testing in a cabinet with 3% CO$_2$, 65% RH, and 25°C while AASL and OPCL remain in a laboratory environment with 0.03% CO$_2$, 65% RH, and 25°C. *Reprinted from Aperador W, de Gutiérrez R, Bastidas D. Steel corrosion behaviour in carbonated alkali-activated slag concrete. Corros Sci 2009;51:2027–33. Copyright © 2009, with permission from Elsevier.*

however, since stainless steel is much more expensive than current steel this option will damage the AACB concrete cost competitiveness against OPC concrete. The use of corrosion inhibitors or even the use of concrete coatings may be a more cost–effective option than stainless steel. Still, further studies are needed to confirm this.

s0045   ## 9.5 CONCLUSIONS AND FUTURE TRENDS

p0085   Research carried out so far in the development of AACB showed that much has already been investigated and also that an environmentally friendly alternative to Portland cement is becoming more viable. However, AACBs still show some shortcomings that need to be addressed so that they can effectively compete against Portland cement. This chapter reviewed some AACB shortcomings, including its costs and carbon dioxide emissions, and also some durability issues like efflorescences, ASR, and corrosion of steel reinforcement. Currently the cost of AACB concretes is located midway between OPC concretes and high-performance concretes. These materials only start to become economically competitive compared to OPC concretes with a strength class. In the short term, the above-cited disadvantage means that the study of AACB applications should focus only on high-cost construction materials. The use of activators based on less-expensive waste feedstocks may reduce AACB costs. This constitutes a research area that deserves priority attention. AACBs have been advertised as low-carbon footprint materials; still, no study has ever confirmed the very low emissions ($0.184 t$ of CO_2 per ton of binder) found by Davidovits. Some studies even found that OPC and AACB have similar carbon footprints. However, and since Davidovits has mentioned that the carbon footprint calculations of sodium silicate used in those studies are wrong, further studies are needed to confirm the real carbon footprint of AACB. The durability of AACB is the most important issue in determining the success of these new materials; still, some durability issues show some worrying results. So far, very few authors have investigated the efflorescence of AACB, which is originated by the fact that Na, K is bounded only weakly in the nanostructure of these materials and is therefore almost completely leachable. Efflorescence can be greatly reduced by the use of hydrothermal curing and the addition of calcium aluminate. However, the use of hydrothermal curing has serious limitations for onsite concrete-placement operations. On the other hand, the use of calcium-based mixtures reduces the acid resistance and raises the chances for the occurrence of the deleterious ASRs. Besides, the use of calcium reduces the global warming emissions advantage over Portland cement. Although ASR has been intensively studied for OPC concrete, the chance that it also may take place in AACB concrete is still scarcely studied. Since calcium plays a significant role in ASR expansion this could mean that studies on how to prevent ASR in calcium-based AACB are needed. The corrosion of steel reinforcement

is one of the causes that influences the structural capability of concrete elements. In OPC binders, steel bars are protected by a passivity layer, due to the high alkalinity of calcium hydroxide. Some studies show that since AACB is prone to alkali leaching, that could lead to a rapidly and disastrous reduction in the pH causing steel corrosion. They also show that the presence of calcium is crucial for having durable steel–reinforced AACB.

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