

Original Research Report

Effect of sodium content as an activator in alkali-activated cement on cement dosage: Evaluation of cement, concrete, and Abrams' law applicability

Pamella Fernandes Figueiredo¹, Sarah Danieli¹, Bruna Luiza Ferreira de Brito¹, Filipe Faria¹, Liberto Züge², Erich David Rodriguez², Márlon Longhi¹, * 

¹ Circlua S.A., Belo Horizonte, Brazil

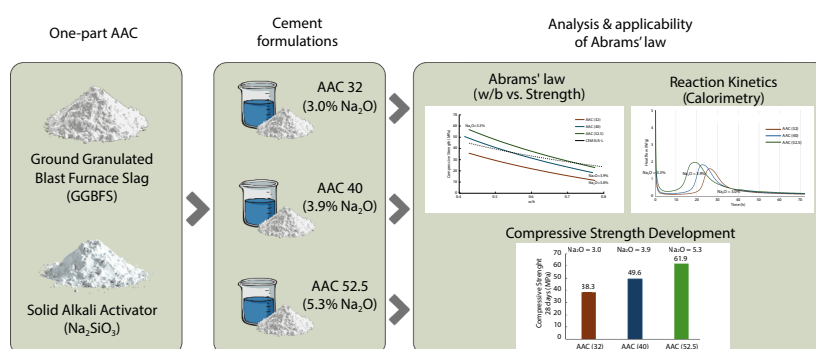
² Department of Structures and Civil Construction, Universidade Federal de Santa Maria (UFSM), Brazil

Abstract: Although research on alkali-activated cements has progressed, large-scale application remains challenging due to a lack of established companies, despite the current interest in the development of one-part alkali-activated cements for different applications. Scale-up production also depends on validating the mechanical and durability properties of the associated raw materials, and the understanding of dosage parameters and physical behavior is a key factor for the advancement of technology.

One-part alkali-activated cements typically consist of ground granulated blast furnace slag as the precursor, with the alkaline activator in solid form, finely ground and mixed with the slag. The solid activator is a decisive factor in the reactivity of the cement, rheological properties in the fresh state, and in the strength development over time in the hardened state. For its widespread application in the construction industry, the alkali-activated cement must be easily used in the production of concrete with different strength levels. Portland cement concrete mix design, a well-known concept widely applied in structural design, is based on Abrams' law, which correlates mechanical strength with the water-to-binder (w/b) ratio. Although the water content also plays a role in the strength of alkali-activated concrete, the concentration and type of activator make this correlation even more complex. The objective of this study is to evaluate the effect of mixing water content on concrete produced with three different types of one-part alkali-activated cements. These three cements were manufactured in a pilot-scale plant, where the activator was adjusted to achieve different alkali concentrations. The alkali content directly influences the strength and reaction rate both in cement and concrete. The behavior of alkali-activated cement is different from ordinary Portland cement in relation to the Abrams' curve, mainly in terms of the inclination of the curve with respect to the w/b ratio; however, for adequate design of this type of concrete, other information such as Na_2O content and $\text{H}_2\text{O}/\text{Na}_2\text{O}$ ratio must be considered.

Keywords: alkali-activated cement, one-part alkali-activated cement, Abrams' law, mechanical behavior

Citation: P. F. Figueiredo, S. Danieli, B. L. F. de Brito, et al. Effect of sodium content as an activator in alkali-activated cement on cement dosage: Evaluation of cement, concrete, and Abrams' law applicability. *Materials Reports: Solidwaste and Ecomaterials*, 2026, 2: 9520030. <https://doi.org/10.26599/MRSE.2026.9520030>.



*Correspondence to M. Longhi, marlonlonghi@gmail.com

Received 1 March 2026; Received in revised form 8 June 2026; Accepted 12 July 2026

©2026 The Authors. Publishing services by Tsinghua University Press. This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>)

1. Introduction

As the demand for concrete continues to rise^[1], sustainable alternatives to traditional Portland cement are being extensively researched^[2,3]. Among these alternatives, alkali-activated cement (AAC) has emerged as a promising material due to its potentially lower carbon footprint and comparable mechanical properties^[4,5]. Alkali-activated cements can be produced by optimally proportioning a finely ground amorphous aluminosilicate mineral with an alkaline activator consisting mainly of hydroxides or silicates of sodium and/or potassium^[6]. Among the most used precursors are ground granulated blast furnace slag, fly ash, and metakaolin, with the slag offering the best technical and economic advantages, as well as greater availability, compared to the other precursors^[7,8]. The hardening process of alkali-activated cement is very different from that of Portland cement, which gains compressive strength as a result of cement hydration. In the case of alkali-activated cements, there is initially a dissolution of the precursor, followed by polycondensation and the formation of products such as hydrated calcium silicates and/or silicate gels, better known as C-A-S-H and N-A-S-H phases^[8,9]. This results in unique strength development characteristics.

Alkali-activated material (AAM) is a broader term that encompasses all systems where a solid aluminosilicate precursor reacts with an alkaline source to form hardened cementitious networks with distinct reaction products depending on precursor chemistry^[10]. Alkali-activated cement (AAC) is a sub-category of AAM typically associated with calcium-rich precursors (e.g., slag), which yield calcium (sodium) aluminosilicate hydrate (C-(N)-A-S-H) as the main gel and are commonly referred to as geopolymers^[11]. In contrast, low-calcium systems form a sodium aluminosilicate hydrate (N-A-S-H) gel^[12]. Because the present study uses a slag-rich formulation, the binding phase is expected to be predominantly C-(N)-A-S-H^[13]. This distinction is critical, as C-(N)-A-S-H gels exhibit greater space-filling ability and contribute to a denser, stronger matrix, especially with increasing alkali (Na_2O) content^[14].

These reaction processes depend directly on the pH of the medium to initiate dissolution. Thus, regarding concrete application, several studies have shown that AACs tend to have lower early strength compared to ordinary Portland cement (OPC) but exhibit superior long-term strength development. For example, a study by Provis et al.^[15] found that while OPC achieved 60% of its 28-day strength within 3 d, AACs typically required up to 7 d to reach comparable levels. However, at 28 d, AACs often surpassed OPC in compressive strength due to their denser microstructure and higher degree of reaction^[6].

The influence of the water-to-binder (w/b) ratio is also crucial. Water's role in AAC is chiefly as a reaction medium and pore former rather than a stoichiometric participant in hydrate formation as in OPC^[6]. Therefore, the chemistry of the activator, governed by alkali dosage (e.g., Na_2O content of binder) and silicate modulus ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$), can amplify or offset water's effect.

However, in the production of concrete manufactured with alkali-activated cements, the concrete's performance does not depend exclusively on activation parameters (such as alkali concentration and soluble silicate content). Therefore, the amount of mixing water, the proportion of aggregates, and the consumption of cementitious material per cubic meter of concrete must also be considered. In the case of Portland cement concretes, Abrams' law has a primary impact on performance because the water-to-cement ratio defines both workability in the fresh state and mechanical strength. Abrams' law is a well-established concept in ordinary Portland cement (OPC) concrete technology, stating that compressive strength is inversely proportional to the water-to-binder (w/b) ratio^[16]. However, the principle applies differently to AAC. For AAC, the literature generally reports a similar behavior, with an inverse relationship between compressive strength and total water content, since excess water increases capillary porosity within the hardened matrix. Experimental data show that AAC concretes with a w/b of 0.4 exhibit the highest strength-to-binder efficiency, while increasing w/b beyond 0.6 leads to significant strength reduction^[17] and a steeper Abrams' curve, meaning their strength is more sensitive to water content variations than OPC^[7]. This is likely due to differences in reaction kinetics and AAC's ability to form denser gel networks, even at slightly higher w/b ratios^[4]. Considering a highly reactive aluminosilicate precursor in AAC, mechanical strength is mainly governed by a combination of parameters: alkali dosage, silicate modulus, and curing conditions. Hardjito & Rangan demonstrated that when the $\text{H}_2\text{O}/\text{Na}_2\text{O}$ molar ratio was held constant, adding water (balanced by a higher NaOH concentration) did not reduce strength, while an increase in the $\text{H}_2\text{O}/\text{Na}_2\text{O}$ ratio reduced mechanical performance, clarifying why a simple "Abrams' curve" may not be sufficient for AAMs^[18]. It should be noted that the above discussion is based on sodium silicate as the alkali source—the most common activator in one-part alkali-activated cements (AACs). However, other solid activators, such as sodium carbonate (Na_2CO_3) and sodium sulfate (Na_2SO_4), are also frequently employed in one-part AAC formulations^[10]. Sodium carbonate offers economic and handling advantages but tends to delay setting and early strength development due to its lower initial alkalinity^[19–20]. Sodium sulfate, in turn, has been shown to reduce drying shrinkage in one-part geopolymers^[21]. While the present study focuses exclusively on sodium silicate, acknowledging these alternative activators is important for contextualizing the applicability of Abrams' law across the broader family of one-part AACs. In slag-rich AAC, lowering the solution/binder or water-to-binder (w/b) ratio and/or raising alkali/silica contents accelerates setting and improves early strength, while higher w/b reliably depresses mechanical performance. In this regard, the interdependence of multiple synthesis or production parameters in AAC hinders the development of a concrete mix design method based on a single variable, as is the case with Portland cement concretes^[22]. The RILEM report synthesizes these findings and explicitly notes the high sensitivity to the w/b ratio in AAC concretes. It emphasizes that AAC mix

design should target workability (flow) at a given strength by coordinating water content with activator dosage and curing, rather than simply transplanting OPC's Abrams-style prescriptions. This advocates for performance-based mix design instead of a prescriptive w/b ratio method^[23].

Despite increasing research on alkali-activated cements (AACs), few studies have examined how variations in sodium content influence concrete performance with regard to Abrams' law. Therefore, this study aims to evaluate different classes of alkali-activated cements—produced by varying the activator content (Na_2O)—in order to correlate the applicability of Abrams' law with the cementitious material's characteristics, mechanical strength, and water-to-binder (w/b) ratio.

2. Materials and methods

2.1. Materials characterization

Ground granulated blast furnace slag was used as the aluminosilicate precursor, along with a solid, finely ground activator produced through a thermal synthesis at 600 °C using sodium hydroxide and quartz to achieve a $\text{SiO}_2/\text{Na}_2\text{O}$ ratio of 1.04. Using this activator and precursor, three alkali-activated cements were produced, in which the ratio between precursor and activator defines the activation concentration. These three systems were classified as AAC (32), AAC (40), and AAC (52.5), where 32, 40, and 52.5 denote the compressive strength class at 28 d in a standardized mortar according to ABNT NBR 7215: 2019^[24]. It should be noted that the increase in strength grade for each AAC is linked to the activation concentration, with AAC (52.5) being the AAC containing the highest activator content. The classes of strength were obtained from the variation of the Na_2O content, which was 3.0%, 3.9%, and 5.3% for AAC (32), AAC (40), and AAC (52.5), respectively. All AACs were produced in a pilot-scale plant in Southeast Brazil. A commercial Portland cement CEM II/A-L was used as reference material. Tables 1 and 2 present the chemical composition and physical properties of the raw materials and the three produced AACs, respectively.

Natural sand (30%) and artificial sand (70%) were used as fine aggregates, with maximum particle sizes of 2.36 mm and

Table 2. Physical characterization of the AACs.

Physical property	AAC (32)	AAC (40)	AAC (52.5)	OPC
D_{10} (μm)	6.9	6.0	4.5	1.5
D_{50} (μm)	19.5	19.4	16.7	9.7
D_{90} (μm)	41.5	49.3	42.1	25.4
D_{av} (μm)	23.2	25.3	21.6	12.4
Density (g cm^{-3})	2.5	2.5	2.5	2.8
Blaine ($\text{cm}^2 \text{g}^{-1}$)	3622	3915	3870	5151

1.18 mm, and specific gravities of 2.67 g cm^{-3} and 2.69 g cm^{-3} , respectively. The coarse aggregate consisted of gneiss crushed stone with maximum nominal sizes of 9.5 mm and 19 mm, and specific gravities of 2.59 g cm^{-3} and 2.63 g cm^{-3} , respectively, according to the physical and granulometric characterization of the materials.

2.2. Alkali-activated cement and concrete production and evaluation

The mechanical strength of the three AACs was characterized according to ABNT NBR 7215: 2019^[24] by producing mortars with a cement-to-sand ratio of 1:3 and a water-to-cement ratio of 0.48. Cylindrical specimens measuring 50 mm in diameter and 100 mm in height were prepared and cured at 95% relative humidity and 23 °C. Compressive strength was determined at 1, 3, 7, and 28 d using a universal testing machine (InterMetric/iM-300) with a loading rate of $0.25 \pm 0.05 \text{ MPa s}^{-1}$ (in accordance with ABNT NBR 7215: 2019)^[24]. To evaluate the reactivity of the AACs, isothermal calorimetry tests were performed using a TAM Air calorimeter (TA Instruments) at 25 °C. Pastes were prepared with a water-to-cement ratio of 0.5, and approximately 4.8 g of paste was placed into the glass ampoules of the calorimeter to measure the heat released over a period of 72 h.

The setting time was determined according to ABNT NBR 16607: 2018^[26] using the Vicat apparatus. A cement paste of normal consistency was prepared and placed in a standardized mold. The initial setting time was recorded when the Vicat needle (1.13 mm, 300 g) penetrated 25 mm from the base. The final setting time was reached when the needle left no visible mark. The test was conducted at 25 ± 2 °C and relative humidity > 50%.

Concrete mixtures were proportioned following the conceptual framework of Abrams' law, in which compressive strength is evaluated as a function of the water-to-binder (w/b) ratio under controlled workability conditions. For each binder system, a series of mixtures was designed by systematically reducing the binder content while maintaining a nearly constant slump ($14 \pm 2 \text{ cm}$)^[27], adjusted exclusively by the addition of water and without the use of chemical admixtures. This approach resulted in a controlled increase in the w/b ratio across mixtures, enabling the construction of strength- w/b relationships analogous to Abrams-type curves. All mixtures were produced and cured according to ABNT NBR 12821: 2009^[28], with curing conducted at 23 ± 2 °C and 95% relative humidity. The resulting mixture proportions are summarized in Table 3.

Flexural strength^[29], indirect tensile strength^[30], and tangent modulus of elasticity^[31] were also determined.

Table 1. Chemical characterization of raw materials and AACs (%).

Oxide	Raw materials		Alkali-activated cement			OPC
	Precursor	Activator	AAC (32)	AAC (40)	AAC (52.5)	
SiO_2	36.6	49.3	37.0	37.1	37.3	18.6
Al_2O_3	11.0	-	10.6	10.4	10.1	4.6
Fe_2O_3	2.0	0.33	1.4	1.5	1.7	2.9
CaO	43.0	0.49	39.5	39.1	37.7	63.5
MgO	5.2	-	5.0	4.9	4.7	0.2
TiO_2	0.5	0.02	0.4	0.4	0.4	0.3
Na_2O	0.7	47.5	3.0	3.9	5.3	-
K_2O	0.0	-	0.4	0.4	0.4	-
MnO	0.7	-	0.5	0.5	0.5	-
LOI*	0.5	-	1.3	4.1	4.7	4.9

*Loss on ignition at 1050 °C^[25].

Table 3. Summary of concrete mixture proportions (kg m⁻³ of concrete).

Material/parameter	AAC (32)				
	32-a	32-b	32-c	32-d	32-e
AAC	500	400	333	286	250
Fine aggregate	676	772	837	883	918
Coarse aggregate	962	959	958	956	955
Water	200	191	189	191	195
w/b	0.40	0.48	0.57	0.67	0.78
Slump (cm)	16.0	15.0	16.0	16.0	16.0

Material/parameter	AAC (40)				
	40-a	40-b	40-c	40-d	40-e
AAC	500	400	333	286	250
Fine aggregate	676	772	837	883	918
Coarse aggregate	962	959	958	956	955
Water	208	195	188	191	192
w/b	0.42	0.49	0.56	0.67	0.77
Slump (cm)	16.0	16.0	16.0	15.5	15.0

Material/parameter	AAC (52.5)				
	52.5-a	52.5-b	52.5-c	52.5-d	52.5-e
AAC	500	400	333	286	250
Fine aggregate	676	772	837	883	918
Coarse aggregate	962	959	958	956	955
Water	214	196	191	189	193
w/b	0.43	0.49	0.57	0.66	0.77
Slump (cm)	15.5	16.0	16.0	15.5	16.0

3. Results

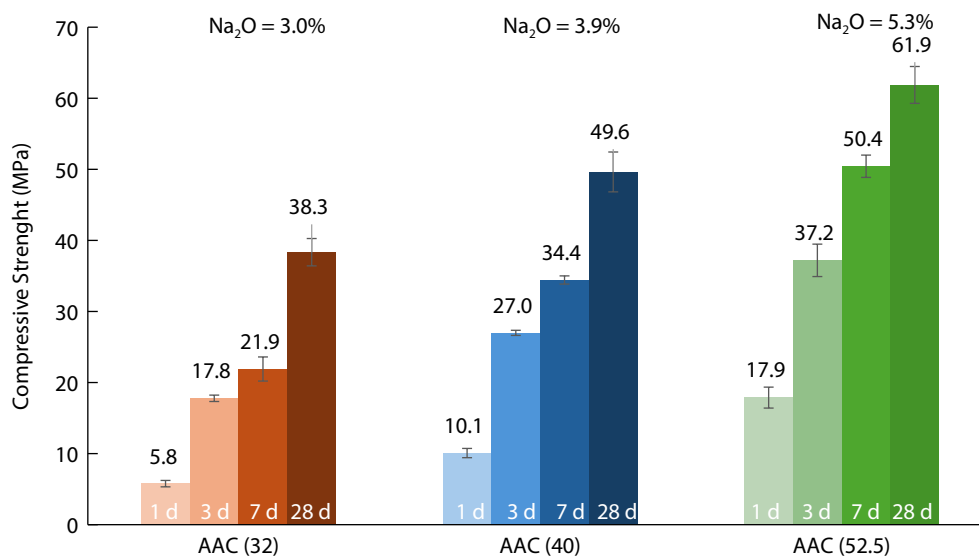
3.1. Alkali-activated cement characteristics

3.1.1. Compressive strength

Fig. 1 shows the compressive strength development over time for the AAC types evaluated. All AACs exhibit a progressive increase in strength, with AAC (52.5) showing the highest values, followed by AAC (40) and AAC (32), as expected. At 1 d, AAC (52.5) reaches 17.9 MPa, 77% higher than AAC (40) (10.1 MPa) and three times higher than AAC (32) (5.8 MPa), indicating a faster reaction for this AAC class. The final

strengths follow the same trend. AAC (52.5) surpasses 50 MPa by 7 d, making it suitable for applications requiring early strength gain and fast formwork removal.

In general, AAC (52.5) demonstrates superior early and final strength, making it ideal for high-performance applications. Lower-class types (AAC (32) and AAC (40)) develop strength more gradually, making them more suitable for general construction and cost-effective applications. This can be explained by the higher activator content, which increases the alkalinity of the system, enhancing the dissolution of the slag precursor and accelerating the precipitation of reaction

**Fig. 1.** Compressive strength of AACs.

products such as C-(A)-S-H and N-(A)-S-H gels. These mechanisms are well-documented in the literature as essential for strength gain in alkali-activated systems^[15,32].

3.1.2. Heat of reaction

Isothermal calorimetry results (Fig. 2 and Table 4) provide essential insights into the reaction kinetics of the AAC types. The heat flow curve is directly linked to the reaction rate. AAC (52.5) exhibits an earlier and higher heat flow peak, indicating a faster dissolution of reactive species and accelerated gel formation. In contrast, AAC (32) shows a delayed and lower peak, suggesting slower dissolution and polymerization process. This difference in reaction rates highlights the influence of sodium content on the reaction process, with higher-strength AAC reacting more rapidly due to their higher alkalinity and greater reactivity.

The cumulative heat releases show the overall progress of the reaction. AAC (52.5) generates the highest cumulative heat (Table 4), indicating a greater reaction extent and more reaction products. AAC (32) exhibits the lowest total heat, indicating slower overall reaction progress, linked to lower energy release. The AACs with higher reactivity, such as AAC (52.5), display a more rapid reaction and higher total heat release, which is consistent with their faster strength development.

When comparing the calorimetry data with the compressive strength results, a clear correlation can be identified (Fig. 3). The AAC (52.5), which showed the highest heat flow and total heat release (for the period of 72 h), also exhibited the most rapid strength gain, surpassing 50 MPa by 7 d and reaching 61.9 MPa at 28 d. This confirms that a higher hydration rate leads to faster strength development. Conversely, AAC (32), which had the lowest heat flow and total heat, demonstrated the slowest strength gain, indicating that its delayed hydration process results in a more gradual increase in mechanical performance. These findings highlight the strong connection between hydration kinetics and the mechanical properties of AAC, emphasizing the importance of selecting the appropriate AAC type based on specific structural and performance requirements. With this, it is possible to predict the strength and heat of reaction from the sodium content used in the systems. As reported previously, the Na₂O content plays a key role in the kinetics and extent of reaction^[33,34].

3.1.3. Setting time

The setting time test results confirm the influence of sodium content in the activators on the hardening behavior of the AAC paste over time. Fig. 4 illustrates the needle displacement over time, indicating when the paste begins to lose fluidity and solidify. The results demonstrate that AAC with higher

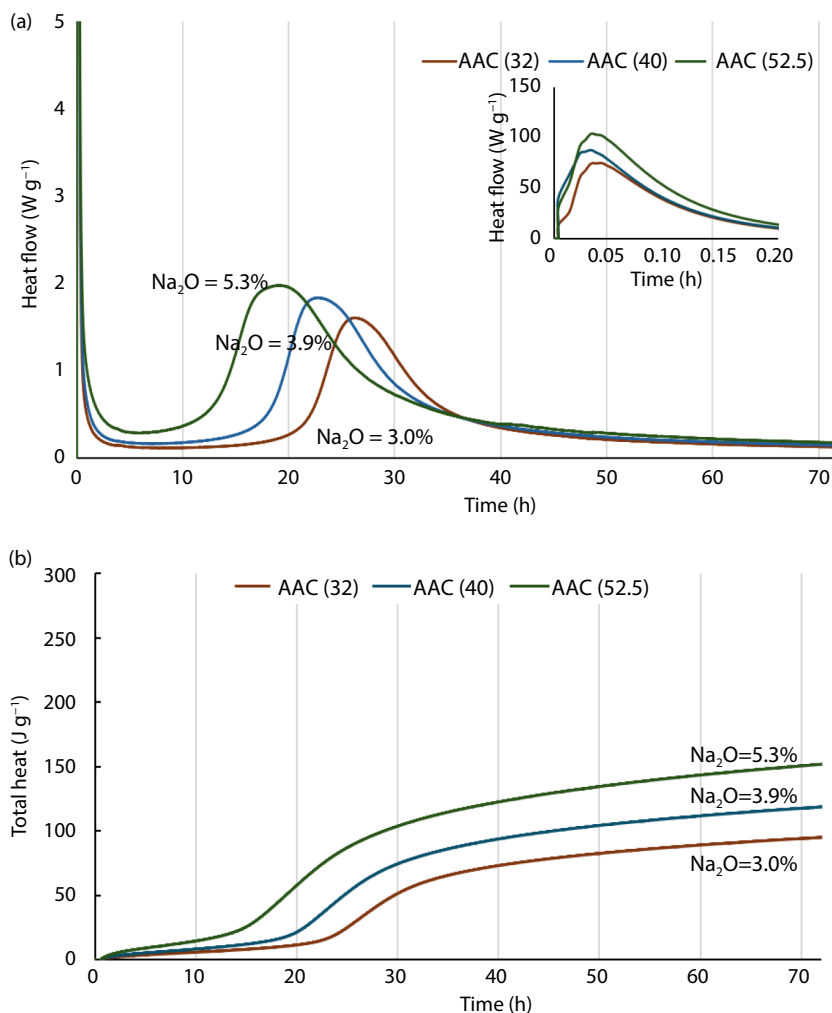
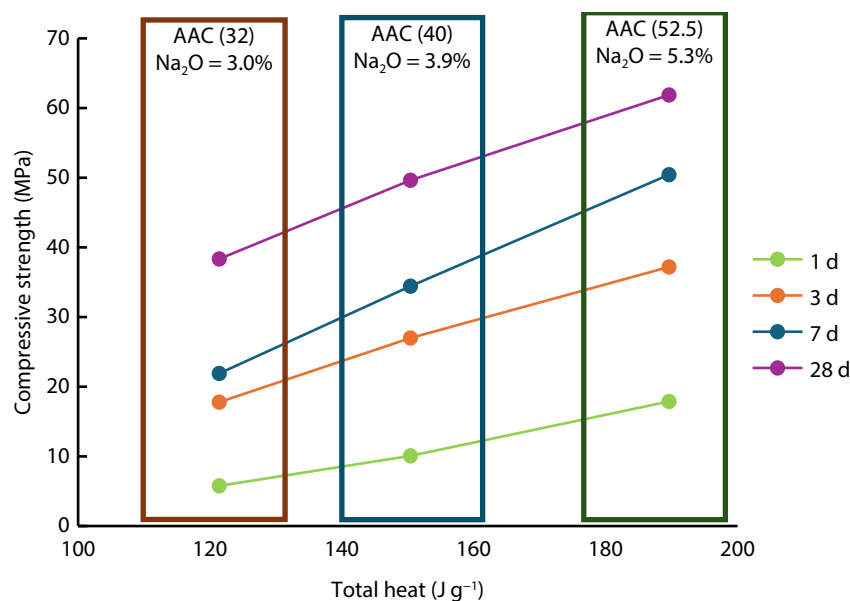
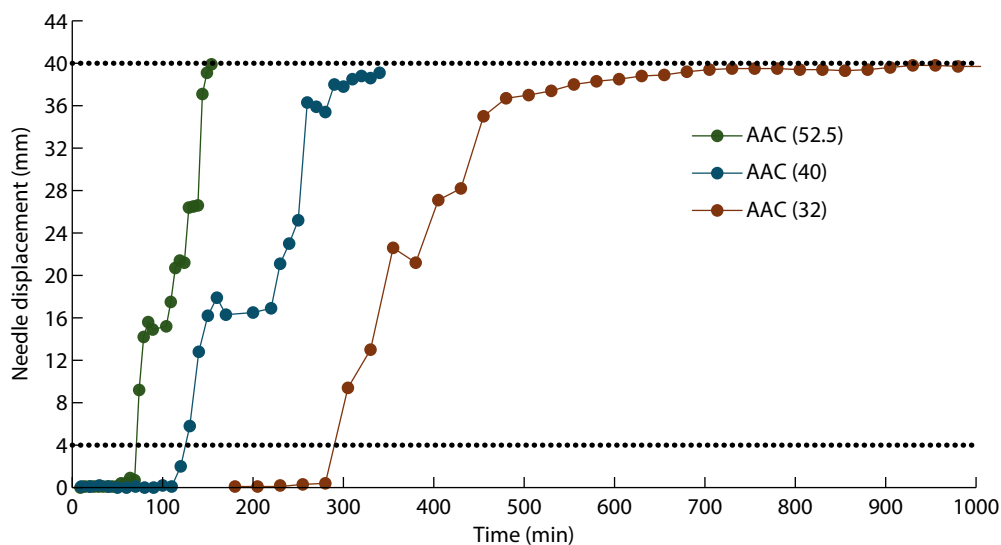


Fig. 2. Calorimetric analysis of AACs: (a) heat flow, (b) total heat.

Table 4. Main parameters of calorimetric analysis for AACs.

Cement	Maximum heat released (mW g ⁻¹)	Accumulated heat (J g ⁻¹)	Time for maximum peak (h)	Minimum heat released (mW g ⁻¹)	End of latency time (h)
AAC (32)	1.60	121.4	26.3	0.11	8.0
AAC (40)	1.83	150.4	22.9	0.16	7.3
AAC (52.5)	1.97	189.6	19.4	0.23	6.2

**Fig. 3.** Correlation between total heat and compressive strength of AACs.**Fig. 4.** Setting time of AACs.

sodium content ($\text{Na}_2\text{O} = 5.3\%$, AAC (52.5)), exhibits shorter initial and final setting times (1 h 10 min and 2 h 34 min, respectively), whereas cements with lower sodium content ($\text{Na}_2\text{O} = 3.0\%$, AAC (32)), take significantly longer to set (4 h 50 min for the initial and 15 h 30 min for the final setting), as shown in Table 5. This trend is consistent with the calorimetry data, which showed that higher-strength AAC (AAC (52.5)) releases heat more rapidly, indicating faster hydration reactions and an accelerated setting process. Therefore, the higher the sodium content, the faster the dissolution of components and the formation of reaction products, reducing the time

Table 5. Setting time of AACs.

Cement	Initial setting time	Final setting time
AAC (32)	4 h 50 min	15 h 30 min
AAC (40)	2 h 10 min	6 h 00 min
AAC (52.5)	1 h 10 min	2 h 34 min

required for the paste to reach rigidity. This characteristic is particularly relevant for applications that require rapid form-work removal or early strength development, although it may also impact workability and the available handling time

of the mixture. This behavior aligns with prior findings that increased sodium levels reduce latency periods by accelerating silicate activation and gel precipitation^[35].

3.2. Concrete performance with different AAC types

3.2.1. Concrete performance with AAC (32)

Fig. 5 illustrates the compressive strength evolution of the dif-

ferent concrete formulations (Table 3), all using AAC (32). All mixtures show progressive strength gain over time, but the rate of development varies with the AAC content. Mixtures with higher AAC content and lower w/b (32-a and 32-b) achieve higher early and final strength, while mixtures with lower AAC content and higher w/b (32-d and 32-e) exhibit very low early strength, with 0 MPa at 1 d.

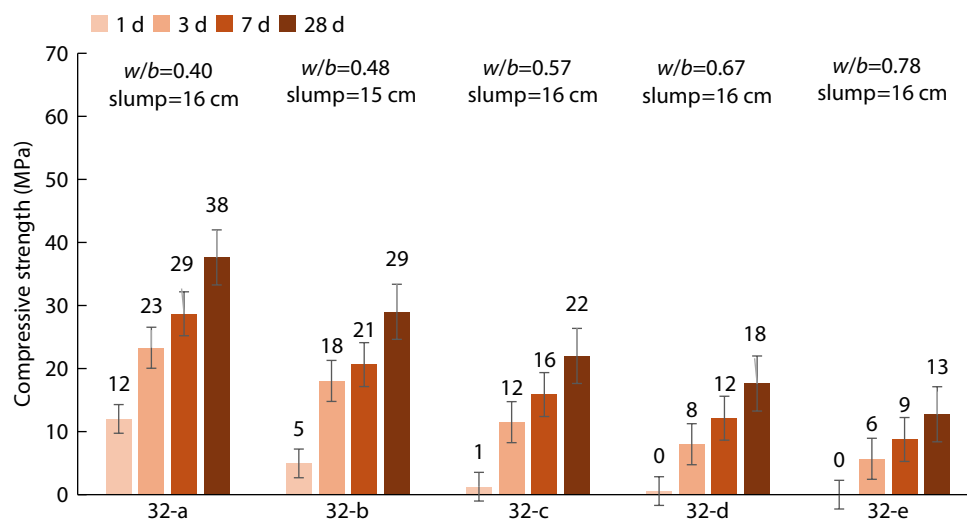


Fig. 5. Compressive strength of concrete containing AAC (32) at 1, 3, 7, and 28 d.

The w/b ratio strongly influences mechanical performance. 32-a achieved the highest strength (38 MPa at 28 d), confirming that a lower water content promotes a denser and stronger cementitious matrix. The strength decreases as w/b increases, with 32-e ($w/b = 0.78$) performing the worst (13 MPa at 28 d). Additionally, only 32-a and 32-b show significant early strength, making them suitable for applications requiring rapid formwork removal and early structural performance.

Additional mechanical property tests were carried out on concrete produced with an intermediate water-to-binder ratio (32-c) (Table 3), and the results are presented in Table 6. The flexural strength and tensile strength at diametral compression results are consistent, given the moderate compressive strength. The tangent modulus of elasticity of 28.2 GPa indicates a concrete mix with acceptable stiffness and deformation resistance.

Table 6. Additional mechanical properties of concrete containing AAC (32-c) at 28 d.

Additional mechanical properties	Results
Flexural strength (MPa)	5.9
Tensile strength at diametral compression (MPa)	2.3
Tangent modulus of elasticity (GPa)	28.2

3.2.2. Concrete performance with AAC (40)

Fig. 6 shows the compressive strength evolution over time for different concrete formulations using AAC (40), indicating progressive gain, with mixtures that have lower w/b achieving better mechanical performance. Like AAC (32), formulations a and b exhibited the highest strength values, while mix-

tures with higher w/b ratios (40-d and 40-e) show significantly lower strength gain. The influence of the w/b ratio (associated also with the AAC content) is evident, as an increase in w/b leads to a significant reduction in final strength. Additionally, higher w/b mixtures showed very low early strength (0 MPa at 1 d), which could compromise applications requiring rapid formwork removal.

The additional mechanical tests for 40-c (Table 7) demonstrate that this formulation, beyond having a good balance between strength and workability, possesses good performance on tensile strength and good structural stiffness, due to its tangent modulus of elasticity of 29.3 GPa.

When comparing the results of AAC (40) and AAC (32), AAC (40) consistently outperforms AAC (32) in all formulations, especially those with lower w/b ratios, since it reaches strength values approximately 10 MPa higher than its AAC (32) counterparts. Additionally, AAC (40) achieved faster early strength gain, which can be advantageous for applications requiring early formwork removal. This difference can be attributed to the higher reactivity of AAC (40) and higher sodium (Na_2O) content in the cement, provided by the added activator, leading to more efficient mechanical development and producing stronger and more durable concrete.

3.2.3. Concrete performance with AAC (52.5)

Fig. 7 demonstrates results with AAC (52.5). As observed in lower-class cements, w/b directly impacts mechanical performance. Formulations a and b exhibit the best mechanical performance, while formulations with higher w/b ratios (d and e) show very low early strength (0 to 2 MPa at 1 d). This trend reaffirms the inverse relationship between water content and the development of mechanical strength, as higher water con-

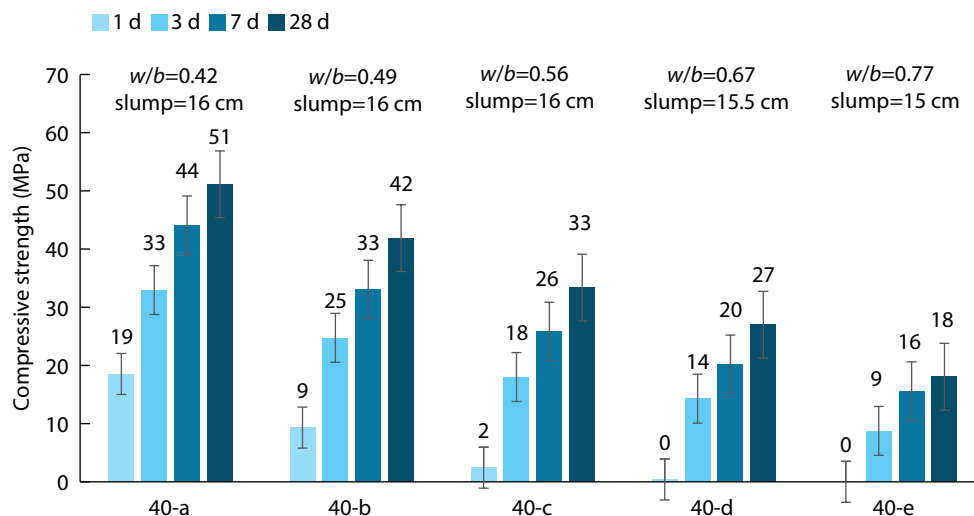


Fig. 6. Compressive strength of concrete containing AAC (40) at 1, 3, 7, and 28 d.

Table 7. Additional mechanical properties of concrete containing AAC (40-c) at 28 d.

Additional mechanical properties	Results
Flexural strength (MPa)	6.5
Tensile strength at diametral compression (MPa)	3.1
Tangent modulus of elasticity (GPa)	29.3

tent increases porosity in the AAC matrix, thereby reducing final strength.

Additional data in Table 8 for the 52.5-c formulation indicate good structural performance, with a flexural strength of 7.7 MPa and a tensile strength of 3.6 MPa at diametral compression. The elastic modulus of 30.0 GPa suggests a rigid structure suitable for high-performance structural applications.

Comparing the results of AAC (52.5) with AAC (40) and AAC (32), it is evident that AAC (52.5) exhibits significantly superior performance, particularly in terms of early strength gain. At 1 d, AAC (52.5) reaches values above 20 MPa in formu-

lations with lower w/b, whereas AAC (40) and AAC (32) do not exceed 19 MPa and 12 MPa, respectively. This rapid development is highly advantageous for applications requiring fast formwork removal and high early strength. Additionally, at 28 d, the low w/b formulations of AAC (52.5) exceed 50 MPa, while AAC (40) ranges from 18 to 51 MPa, and AAC (32) reaches a maximum of 38 MPa. This difference reinforces the superiority of AAC (52.5) in reactivity and structural performance, making it more suitable for high-performance applications and structures under high mechanical demands.

3.3. Abrams' curves behavior

The Abrams' curve (Fig. 8) illustrates the relationship between compressive strength at 28 d and the w/b ratio for different types of cements (CEM II/A-L, AAC (32), AAC (40), and AAC (52.5)). The general trend observed confirms Abram's law, stating that concrete strength decreases as the w/b ratio increases.

At 28 d, CEM II/A-L shows the lowest strength at low w/b ratios (~0.4–0.5), where the AACs clearly outperform it. As the

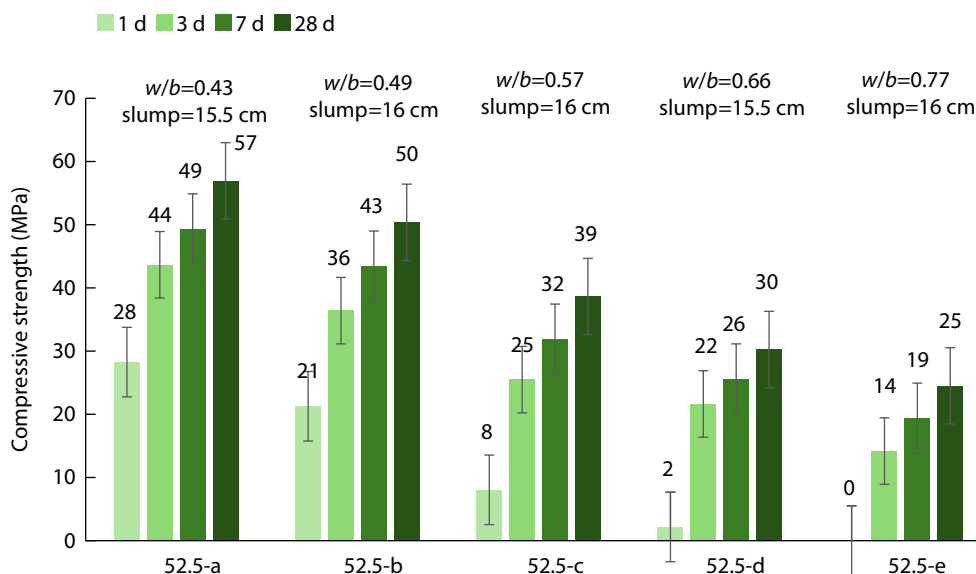
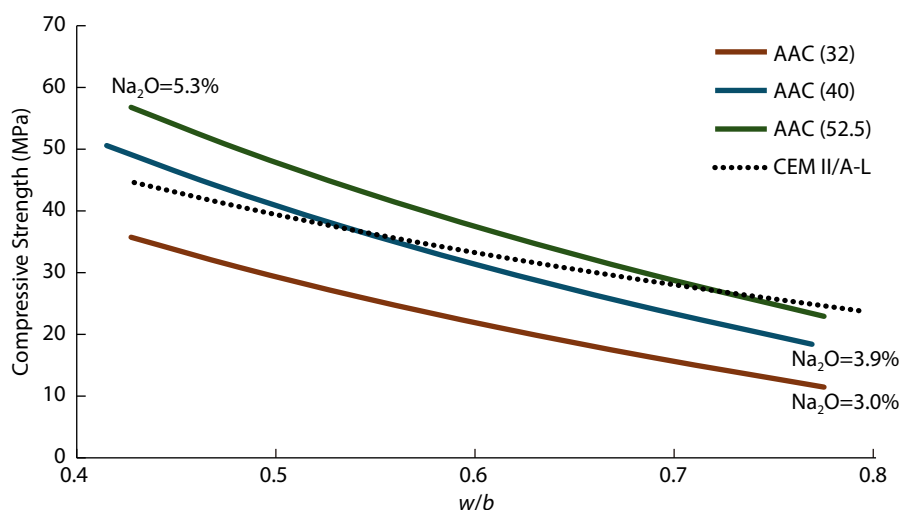


Fig. 7. Compressive strength of concrete containing AAC (52.5) at 1, 3, 7, and 28 d.

Table 8. Additional mechanical properties of concrete containing AAC (52.5-c) at 28 d.

Additional mechanical properties	Results
Flexural strength (MPa)	7.7
Tensile strength at diametral compression (MPa)	3.6
Tangent modulus of elasticity (GPa)	30.0

**Fig. 8.** Abrams' curves of alkali-activated cements at 28 d.

w/b ratio increases, the curves converge: beyond ~ 0.5 , CEM II/A-L matches and then exceeds AAC (32) and AAC (40), reflecting the greater sensitivity of the AACs to mixing water (a steeper Abrams' curve). Although CEM II/A-L reaches lower strengths than the AACs at low w/b , its curve is less steep, so it is comparatively less affected as the w/b ratio increases. Among AACs, AAC (52.5) achieves the highest compressive strength at all w/b ratios, indicating higher reactivity and more efficient mechanical development. AAC (40) shows intermediate performance, ranking above AAC (32) but below AAC (52.5), suggesting a slightly reduced reaction compared to the higher-class AAC.

The impact of the w/b ratio is evident across all formulations. At low w/b ratios (~ 0.4 – 0.5), AACs exhibit superior performance, with AAC (52.5) reaching nearly 60 MPa. At higher w/b ratios (~ 0.5 – 0.8), the strength of all cements decreases, but the reduction is steeper for the AACs: AAC (32) and AAC (40) drop to or below the level of CEM II/A-L, whereas AAC (52.5) retains the highest strength over the range evaluated. This greater water sensitivity is consistent with the dilution of the activator (higher H_2O/Na_2O ratio), which slows the reaction and increases matrix porosity.

The different classes of alkali-activated cement were obtained from the combination of precursor and activator to enable different levels of strength. Thus, for concrete produced with different cements to have the same strength, it is necessary to vary the consumption of cement. Therefore, Fig. 9 shows the amount of cement needed to obtain 1 MPa for each of the cement classes evaluated.

The data show that AAC (52.5) exhibits the lowest binder consumption per MPa, indicating higher efficiency in strength development. This is expected, as higher-class AAC

have a greater proportion of reactive components, allowing them to achieve higher strength with less material. In contrast, AAC (32) shows the highest binder consumption per MPa, meaning it requires more material to achieve the same strength levels as the higher-class AAC, suggesting a less efficient hydration process. AAC (40) follows an intermediate trend, consuming slightly more AAC per MPa than AAC (52.5) and demonstrating moderate efficiency. Interestingly, CEM II/A-L shows a relatively stable consumption trend across different w/b ratios, suggesting that Portland cement is less sensitive to variations in w/b compared to alkali-activated cements.

A comparison between AACs and OPC reveals that AAC (52.5) and AAC (40) are more efficient than Portland cement, consuming less material per MPa; however, at higher w/b ratios (~ 0.7 – 0.8), consumption for AAC (40) surpasses that of CEM II/A-L, suggesting that alkali-activated cements become less efficient when excessive water is added. AAC (32) remains the least efficient AAC across all w/b ratios, consistently consuming more AACs per MPa than Portland cement and higher-class AACs.

It should be noted that the binder consumption per MPa is a purely mechanical efficiency indicator and should not be directly interpreted as a proxy for environmental or economic performance. Although AAC (52.5) exhibits the lowest binder consumption per MPa, it also contains the highest Na_2O content (5.3%) due to the larger proportion of solid sodium silicate activator. The production of sodium silicate is energy-intensive and generates significant CO_2 emissions, which may partially or fully offset the benefits of lower binder consumption. Therefore, while this metric is useful for comparing the reactivity of different AACs, a complete life

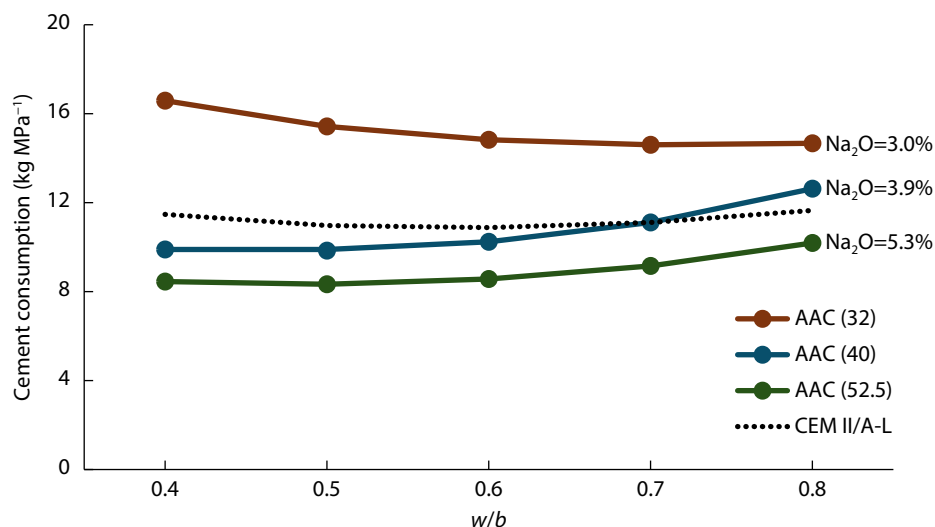


Fig. 9. Binder consumption per unit compressive strength (kg MPa⁻¹) for different cements at 28 d.

cycle assessment (LCA) is necessary to evaluate the actual environmental and cost advantages of each AAC class. Future studies should incorporate such analyses to support material selection in sustainable construction.

Although Abrams' curve is a valuable tool for the mix design of alkali-activated concrete, it is not sufficient on its own, and other characteristics must also be considered. The activator content, represented by the Na₂O content, is a determining factor for mechanical performance for each class of AAC, and the H₂O/Na₂O ratio is determinant for a better understanding of this type of concrete with the variation in water consumption. These characteristics will be better discussed in the following sections.

3.4. Effect of Na₂O content and H₂O/Na₂O ratio

Although Abrams' curve remains a useful and practical approach for the mix design of alkali-activated concretes, similarly to conventional Portland cement systems, the mechanical behavior of AACs cannot be fully interpreted solely as a function of the water-to-binder (w/b) ratio. In alkali-activated systems, the activator concentration also plays a fundamental role in reaction kinetics and strength development. Therefore, in addition to the traditional Abrams' relationship, the H₂O/Na₂O ratio can be used as a complementary parameter for understanding and designing AAC mixtures, since it incorporates the chemical effect of activator dilution into the interpretation of compressive strength development.

The difference in the dosage of the AAC is exclusively due to the variation of the Na₂O content in the AAC composition from the addition of activator (sodium silicate base with $M_s = 1.04$). For the w/b range evaluated, the AACs outperform Portland cement (CEM II/A-L) at low w/b ratios (Fig. 8). The increasing performance trend AAC (32) < AAC (40) < AAC (52.5) reflects the direct influence of Na₂O content on compressive strength (Fig. 10), showing that higher activator concentrations lead to superior mechanical performance across the w/b range evaluated.

An increase in sodium content enhances the reactivity of alkali-activated cements because higher concentrations of Na₂O raise the alkalinity of the pore solution, promoting

faster dissolution of the amorphous aluminosilicate or slag precursors and accelerating the formation of C-(A)-S-H and N-A-S-H gels. This behavior was previously confirmed by the calorimetric analysis, where AAC (52.5) exhibited higher heat release, shorter latency periods, and faster strength development compared to AAC (32) and AAC (40). Consequently, higher Na₂O contents lead to denser cementitious matrices with lower porosity and superior mechanical performance.

Thus, in the formulation of commercial alkali-activated cements, the Na₂O content becomes a key parameter that governs the binder demand and the final performance of each cement class. Each AAC class, therefore, presents its own dosage behavior and Abrams-type curve, allowing mix designs to be optimized according to the required mechanical performance.

Along the different points of w/b evaluated, the total water volume used per cubic meter of concrete remained relatively constant, while the AAC content progressively decreased, resulting in higher w/b ratios and significantly lower compressive strengths, following an exponential trend (Fig. 11). This behavior indicates that the increase in water content not only affects matrix porosity, as traditionally described by Abrams' law, but also alters the effective concentration of the alkaline activating environment.

In this context, the H₂O/Na₂O ratio provides an important complementary interpretation of AAC behavior. Higher H₂O/Na₂O ratios correspond to more diluted alkaline systems, which slow down the dissolution of the vitreous phases of the precursor and reduce the rate of gel polymerization (N-A-S-H or C-(N)-A-S-H). Literature reports similar trends and emphasizes that higher strengths are obtained when activation occurs under more concentrated Na₂O conditions, which favor the precipitation of compact hydration products, while higher H₂O/Na₂O ratios lead to weaker and more porous matrices^[12,36]. Likewise, excessively diluted solutions lack sufficient ionic strength to effectively dissolve the aluminosilicate precursor^[37].

The underlying mechanisms can be explained by the dependence of precursor dissolution on the pH and ionic con-

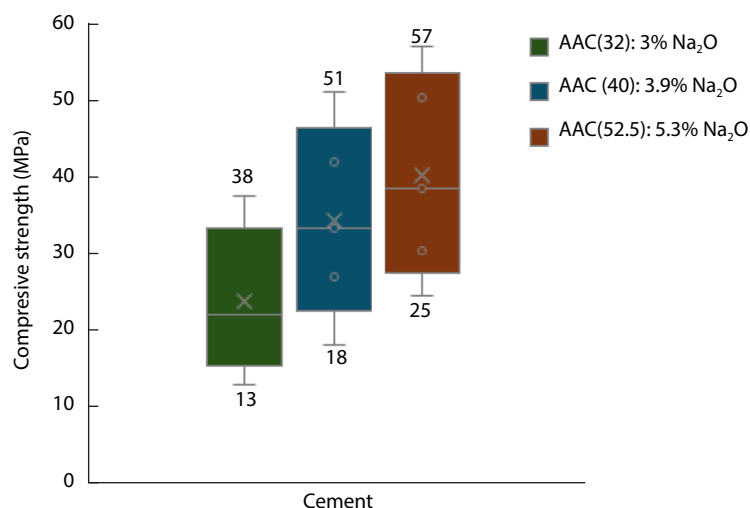


Fig. 10. Compressive strength for cements with different content of Na₂O. In each box, the horizontal line indicates the median and the cross (x) the mean; open circles (o) represent the individual datapoints. The box spans the interquartile range (Q1–Q3) and the whiskers extend to the maximum and minimum values, indicated by the labels.

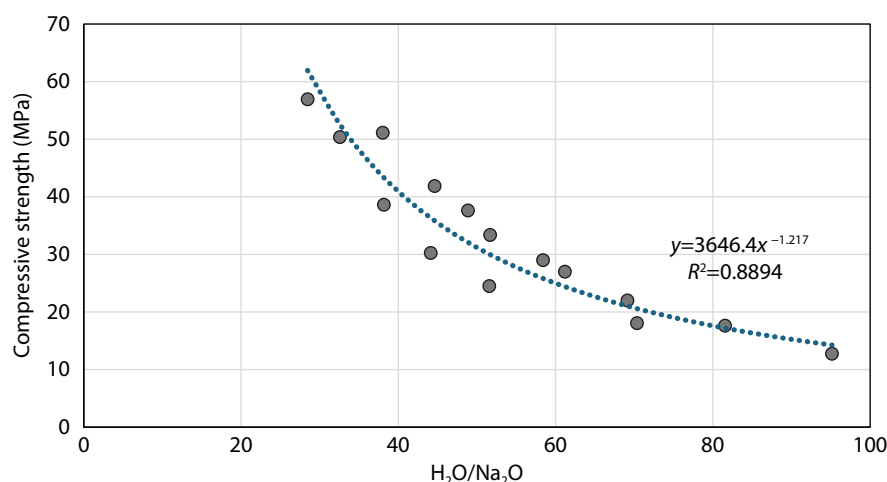


Fig. 11. The relationship between H₂O/Na₂O ratio and compressive strength in concrete.

centration of the pore solution. Higher H₂O/Na₂O ratios reduce the concentration of hydroxyl ions available to attack the Si–O and Al–O bonds of the slag, delaying the release of silicate and aluminate species necessary for gel nucleation and growth^[10,38]. Consequently, the induction period becomes longer, and the polycondensation reactions proceed more slowly, resulting in less cross-linked and more heterogeneous gel structures. Conversely, lower H₂O/Na₂O ratios promote faster dissolution, accelerated gel precipitation, and the formation of denser and more compact matrices with superior mechanical strength^[12,39,40].

Even with AAC compositions with different sodium contents, the H₂O/Na₂O ratio showed a strong correlation with compressive strength. For the evaluated materials, compressive strengths above 40 MPa were generally associated with H₂O/Na₂O ratios lower than 40, while strengths between 20 and 40 MPa were obtained for ratios between 40 and 70.

Therefore, the H₂O/Na₂O ratio does not replace Abrams' curve in concrete mix design but acts as a complementary parameter for alkali-activated systems. While the *w/b* ratio

describes the global water content and its influence on porosity, the H₂O/Na₂O ratio better represents the effective chemical dilution of the activating medium. For commercial one-part AACs, where the Na₂O content is fixed in the cement composition, this parameter helps define the appropriate water demand. In two-part alkali-activated systems, this relationship can additionally support the optimization of activator dosage and binder consumption for a target compressive strength.

4. Conclusions

This study demonstrated that the mechanical performance of one-part alkali-activated cements is strongly governed by the Na₂O content and by the interaction between activator concentration and water content. Higher activator dosages increased cement reactivity, accelerated reaction kinetics, and enhanced compressive strength development, confirming the applicability of an Abrams-type relationship for alkali-activated concretes, although with greater sensitivity to water variations than Portland cement systems. The results

also demonstrated that the $\text{H}_2\text{O}/\text{Na}_2\text{O}$ ratio is an important complementary parameter for interpreting and designing AAC mixtures.

(1) The different AAC strength classes were directly associated with the Na_2O content used in the cement composition. For $\text{H}_2\text{O}/\text{Na}_2\text{O}$ ratios lower than 40, compressive strengths above 40 MPa were generally obtained, while ratios between 40 and 70 resulted in strengths between 20 and 40 MPa. This relationship provides a practical reference for AAC mix design, particularly for systems with fixed Na_2O content.

(2) Higher Na_2O contents also improved cementitious efficiency. AAC (52.5) exhibited lower binder consumption per MPa than AAC (32), indicating that higher activator concentrations promote more efficient strength development due to the greater extent of reaction confirmed by calorimetric analysis.

Overall, the results demonstrate that the compressive strength of one-part alkali-activated concretes is governed by the combined interaction between the w/b ratio, Na_2O content, and $\text{H}_2\text{O}/\text{Na}_2\text{O}$ ratio, highlighting the need for integrated mix design approaches for AAC systems rather than relying exclusively on conventional Portland cement-based parameters.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be available from the corresponding author upon request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pamella Fernandes Figueiredo, Sarah Danieli, Bruna Luiza Ferreira de Brito, Filipe Faria, and Márlon Longhi are employed by Circlua S.A., Brazil.

Author contribution statement

Pamella Fernandes Figueiredo: Investigation, Formal analysis, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Sarah Danieli:** Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Bruna Luiza Ferreira de Brito:** Investigation, Formal analysis, Methodology, Data curation. **Filipe Faria:** Investigation, Formal analysis, Methodology, Data curation. **Liberto Züge:** Investigation, Formal analysis, Data curation, Writing – original draft. **Erich David Rodriguez:** Writing – review & editing. **Márlon Longhi:** Methodology, Data curation, Writing – original draft, Writing – review & editing, Project administration.

Use of AI statement

None.

References

- [1] Portland Cement Association. Roadmap to carbon neutrality. Available at: [https://www.cement.org/wp-content/uploads/](https://www.cement.org/wp-content/uploads/2024/05/Roadmap_Jan2024.pdf)

[2024/05/Roadmap_Jan2024.pdf](https://www.cement.org/wp-content/uploads/2024/05/Roadmap_Jan2024.pdf) (cited 24 Feb. 2026).

- [2] Gartner, E., Hirao, H. A review of alternative approaches to the reduction of CO_2 emissions associated with the manufacture of the binder phase in concrete. *Cement and Concrete Research*, **2015**, 78: 126–142. <https://doi.org/10.1016/j.cemconres.2015.04.012>.
- [3] Favier, A., De Wolf, C., Scrivener, K., et al. A sustainable future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050. ETH Zurich and EPFL, **2018**.
- [4] Provis, J. L. Alkali-activated materials. *Cement and Concrete Research*, **2018**, 114: 40–48. <https://doi.org/10.1016/j.cemconres.2017.02.009>.
- [5] Passuello, A., Rodríguez, E. D., Hirt, E., et al. Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators. *Journal of Cleaner Production*, **2017**, 166: 680–689. <https://doi.org/10.1016/j.jclepro.2017.08.007>.
- [6] Duxson, P., Fernández-Jiménez, A., Provis, J. L., et al. Geopolymer technology: The current state of the art. *Journal of Materials Science*, **2007**, 42(9): 2917–2933. <https://doi.org/10.1007/s10853-006-0637-z>.
- [7] Fernández-Jiménez, A., Cristelo, N., Miranda, T., et al. Sustainable alkali activated materials: Precursor and activator derived from industrial wastes. *Journal of Cleaner Production*, **2017**, 162: 1200–1209. <https://doi.org/10.1016/j.jclepro.2017.06.151>.
- [8] Rossi, L., Miranda de Lima, L., Sun, Y., et al. Future perspectives for alkali-activated materials: From existing standards to structural applications. *RILEM Technical Letters*, **2023**, 7: 159–177. <https://doi.org/10.21809/rilemtechlett.2022.160>.
- [9] Bernal, S. A., Rodríguez, E. D., Mejía de Gutiérrez, R., et al. Mechanical and thermal characterisation of geopolymers based on silicate-activated metakaolin/slag blends. *Journal of Materials Science*, **2011**, 46(16): 5477–5486. <https://doi.org/10.1007/s10853-011-5490-z>.
- [10] Luukkonen, T., Abdollahnejad, Z., Yliniemi, J., et al. One-part alkali-activated materials: A review. *Cement and Concrete Research*, **2018**, 103: 21–34. <https://doi.org/10.1016/j.cemconres.2017.10.001>.
- [11] Ouyang, X., Ma, Y., Liu, Z., et al. Effect of the sodium silicate modulus and slag content on fresh and hardened properties of alkali-activated fly ash/slag. *Minerals*, **2020**, 10(1): 15. <https://doi.org/10.3390/min10010015>.
- [12] Provis, J. L. Geopolymers and other alkali activated materials: Why, how, and what. *Materials and Structures*, **2014**, 47(1): 11–25. <https://doi.org/10.1617/s11527-013-0211-5>.
- [13] Puertas, F., Martínez-Ramírez, S., Alonso, S., et al. Alkali-activated fly ash/slag cements Strength behaviour and hydration products. *Cement and Concrete Research*, **2000**, 30(10): 1625–1632. [https://doi.org/10.1016/S0008-8846\(00\)00298-2](https://doi.org/10.1016/S0008-8846(00)00298-2).
- [14] Guo, L., Liu, J., Zhou, M., et al. Effect of an alkali activators on the compressive strength and reaction mechanism of coal gangue-slag-fly ash geopolymer grouting materials. *Construction and Building Materials*, **2024**, 426: 136012. <https://doi.org/10.1016/j.conbuildmat.2024.136012>.
- [15] Provis, J. L., Bernal, S. A. Geopolymers and related alkali-activated materials. *Annual Review of Materials Research*, **2014**, 44: 299–327. <https://doi.org/10.1146/annurev-matsci-070813-113515>.
- [16] Abrams, D. A. Design of Concrete Mixtures. Chicago: Portland Cement Association, **1918**.
- [17] van Deventer, J. S. J., Provis, J. L., Duxson, P., et al. Chemical research and climate change as drivers in the commercial adop-

- tion of alkali activated materials. *Waste and Biomass Valorization*, **2010**, 1(1): 145–155. <https://doi.org/10.1007/s12649-010-9015-9>.
- [18] Hardjito, D., Rangan, B. V. Development and properties of low-calcium fly ash-based geopolymer concrete. Research Report GC 1. Perth, Australia: Curtin University of Technology, **2005**.
- [19] Gao, X., Yao, X., Yang, T., et al. Calcium carbide residue as auxiliary activator for one-part sodium carbonate-activated slag cements: Compressive strength, phase assemblage and environmental benefits. *Construction and Building Materials*, **2021**, 308: 125015. <https://doi.org/10.1016/j.conbuildmat.2021.125015>.
- [20] Bernal, S. A., Provis, J. L., Myers, R. J., et al. Role of carbonates in the chemical evolution of sodium carbonate-activated slag binders. *Materials and Structures*, **2015**, 48(3): 517–529. <https://doi.org/10.1617/s11527-014-0412-6>.
- [21] Ma, C., Zhao, B., Wang, L., et al. Clean and low-alkalinity one-part geopolymeric cement: Effects of sodium sulfate on microstructure and properties. *Journal of Cleaner Production*, **2020**, 252: 119279. <https://doi.org/10.1016/j.jclepro.2019.119279>.
- [22] Naqi, A., Delsaute, B., Königsberger, M., et al. Effect of solution-to-binder ratio and alkalinity on setting and early-age properties of alkali-activated slag-fly ash binders. *Materials*, **2022**, 16(1): 373. <https://doi.org/10.3390/ma16010373>.
- [23] Provis, J. L., van Deventer, J. S. J. Alkali Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM. Dordrecht: Springer Netherlands, 2014. <https://doi.org/10.1007/978-94-007-7672-2>.
- [24] Associação Brasileira de Normas Técnicas. Portland cement—Determination of compressive strength of cylindrical test specimens. ABNT NBR 7215: 2019, **2019**.
- [25] Associação Brasileira de Normas Técnicas. Portland cement—Chemical analysis—Part 6 : Determination of loss on ignition. ABNT NBR 17086-6:2023, **2023**.
- [26] Associação Brasileira de Normas Técnicas. Portland cement—Determination of setting times. ABNT NBR 16607: 2018, **2018**.
- [27] Associação Brasileira de Normas Técnicas. Concrete—Slump test for determination of the consistency. ABNT NBR 16889: 2020, **2020**.
- [28] Associação Brasileira de Normas Técnicas. Concrete—Preparation in laboratory—Procedure. ABNT NBR 12821: 2009, **2009**.
- [29] Associação Brasileira de Normas Técnicas. Concrete—Determination of tension strength in flexure of prismatic specimens. ABNT NBR 12142-2010, **2010**.
- [30] Associação Brasileira de Normas Técnicas. Concrete and mortar — Determination of the tension strength by diametrical compression of cylindrical test specimens. ABNT NBR 7222:2011, **2011**.
- [31] Associação Brasileira de Normas Técnicas. Hardened concrete—Determination of elasticity and deformation modulus. ABNT NBR 8522-1:2021, **2021**.
- [32] Bernal, S. A., Mejía de Gutiérrez, R., Provis, J. L. Engineering and durability properties of concretes based on alkali-activated granulated blast furnace slag/metakaolin blends. *Construction and Building Materials*, **2012**, 33: 99–108. <https://doi.org/10.1016/j.conbuildmat.2012.01.017>.
- [33] Criado, M., Fernández-Jiménez, A., Palomo, A. Alkali activation of fly ash: Effect of the $\text{SiO}_2/\text{Na}_2\text{O}$ ratio. *Microporous and Mesoporous Materials*, **2007**, 106(1/2/3): 180–191. <https://doi.org/10.1016/j.micromeso.2007.02.055>.
- [34] Zhang, Z., Provis, J. L., Wang, H., et al. Quantitative kinetic and structural analysis of geopolymers. Part 2. Thermodynamics of sodium silicate activation of metakaolin. *Thermochimica Acta*, **2013**, 565: 163–171. <https://doi.org/10.1016/j.tca.2013.01.040>.
- [35] Zhang, Z., Provis, J. L., Reid, A., et al. Geopolymer foam concrete: An emerging material for sustainable construction. *Construction and Building Materials*, **2014**, 56: 113–127. <https://doi.org/10.1016/j.conbuildmat.2014.01.081>.
- [36] Puertas, F., Fernández-Jiménez, A., Blanco-Varela, M. T. Pore solution in alkali-activated slag cement pastes. Relation to the composition and structure of calcium silicate hydrate. *Cement and Concrete Research*, **2004**, 34(1): 139–148. [https://doi.org/10.1016/S0008-8846\(03\)00254-0](https://doi.org/10.1016/S0008-8846(03)00254-0).
- [37] Palomo, A., Grutzeck, M. W., Blanco, M. T. Alkali-activated fly ashes. *Cement and Concrete Research*, **1999**, 29(8): 1323–1329. [https://doi.org/10.1016/S0008-8846\(98\)00243-9](https://doi.org/10.1016/S0008-8846(98)00243-9).
- [38] Puertas, F., Palacios, M., Manzano, H., et al. C-A-S-H gels formed in alkali-activated slag cement pastes. Structure and effect on cement properties and durability. *MATEC Web of Conferences*, **2014**, 11: 01002. <https://doi.org/10.1051/mateconf/20141101002>.
- [39] Ghafoor, M. T., Rakhimova, N., Shi, C. One part geopolymers: A comprehensive review of advances and key challenges. *Journal of Building Engineering*, **2025**, 111: 113112. <https://doi.org/10.1016/j.jobbe.2025.113112>.
- [40] Hajimohammadi, A., van Deventer, J. S. J. Characterisation of one-part geopolymer binders made from fly ash. *Waste and Biomass Valorization*, **2017**, 8(1): 225–233. <https://doi.org/10.1007/s12649-016-9582-5>.



Pamela Fernandes Figueiredo is a Product Engineer at Circlua (Brazil), contributing to the development and industrial implementation of low-carbon cementitious materials, particularly alkali-activated systems derived from mining residues. She holds a degree in Civil Engineering and a Master's degree in Materials Engineering, and is currently a PhD candidate in Metallurgical, Materials and Mining Engineering at the Federal University of Minas Gerais (UFMG), Brazil. Her research focuses on alkali-activated cements, the valorization of mining, industrial and agro-industrial residues, and concrete durability, aiming to advance clinker-free binders and circular solutions for sustainable construction.



Sarah Danieli is a master's student at Federal University of Rio Grande do Sul (UFRGS, Brazil) and an R&D analyst at Circlua (Brazil). Her research focuses on supplementary cementitious materials, carbon capture, utilization, and storage (CCUS), CO_2 mineralization, activated clays, novel cementitious materials, life cycle assessment and carbon footprint, and alkali-activated materials, aiming at the development of more sustainable construction materials.



Bruna Luiza Ferreira de Brito is an R&D Engineer at Circlua (Brazil). She obtained her Master's degree in Chemical and Biochemical Process Engineering from the Federal University of Rio de Janeiro (UFRJ, Brazil). She has over 10 years of academic and industrial experience in developing low-carbon cementitious materials, with a particular focus on mineral valorization,

supplementary cementitious materials, LC3 systems, and alternative binders. Her expertise includes advanced characterization techniques, especially X-ray diffraction (XRD), as well as rheological assessment of cementitious systems and the study of cement–admixture interactions. Her work also encompasses carbon capture, utilization, and storage (CCUS) strategies applied to the cement industry.



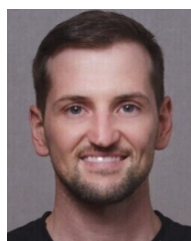
Filipe Faria is Coordinator of the Technical Center at Circlua (Brazil), where he oversees the R&D Laboratory and the Alkali-Activated Materials Pilot Plant, leading research and technological development initiatives in alternative cementitious systems. He holds a BSc and an MSc in Civil Engineering and is currently a PhD candidate at the Federal University of Rio de Janeiro (COPPE/UFRJ). His research focuses on concrete and mortar technology, alkali-activated binders, alternative cementitious materials, and sustainable construction materials. His work integrates experimental investigation and applied research aimed at improving performance, durability, and environmental efficiency in cement-based systems.



Liberto Züge is a master's student at the Federal University of Santa Maria (UFSM, Brazil), working in the field of advanced cementitious materials. His research focuses on alkali-activated cements and geopolymers, with emphasis on concrete durability, particularly carbonation and efflorescence, aiming at the development of more sustainable construction materials.



Erich David Rodriguez is an Assistant Professor at the Federal University of Santa Maria (Brazil), where his research focuses on the development and multi-scale characterization of sustainable cementitious materials. He holds a PhD in Construction Engineering from the Universitat Politècnica de València (Spain) and two master's degrees in construction materials (from Colombia and Spain), with part of his doctoral research conducted at the University of Melbourne (Australia). His work centers on clinker-free binders based on alkali-activated metakaolin, fly ash, and slags, correlating microstructure and performance, particularly under aggressive environments. He is currently involved in research on 3D printing of concrete, including rheology, hardening kinetics, and deposition processes in Portland cement-based and alternative binders.



Márlon Longhi is Head of Sciences at Circlua (Brazil), where he leads the scientific and technological strategy for the development and industrial scaling of low-carbon cementitious materials. He is a civil engineer graduated from the Federal University of Rio Grande do Sul (UFRGS), where he also completed his Master's and Doctorate in Civil Engineering, with part of his doctoral research conducted at the University of Southern Queensland (Australia), with a focus on cementitious materials and alkali-activated cement. His work integrates cement chemistry, mineral processing, thermal activation, and techno-economic assessment to advance clinker reduction and circular industrial symbiosis between the mining and cement sectors.