

Review

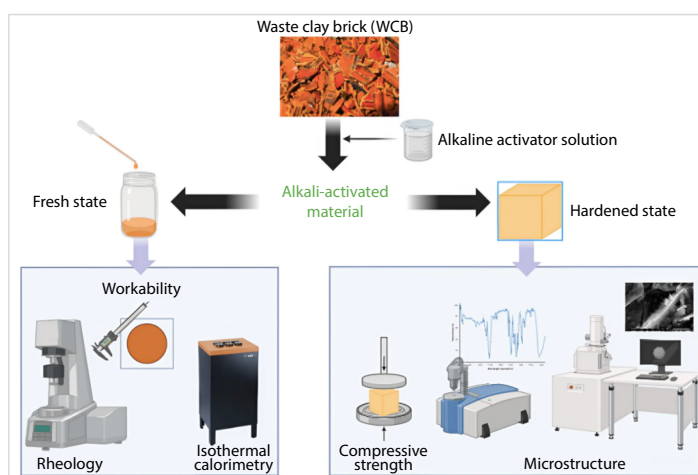
Waste clay brick utilization in alkali-activated materials: A review on fresh and hardened state properties

Ivo de Castro Carvalho^{1,2,*}, Zuhua Zhang³, Ana P. Kirchheim², Heloína N. Costa^{1,4}, Antônio E. B. Cabral¹¹ Department of Structural Engineering and Civil Construction, Post-graduate Program in Civil Engineering (PEC), Universidade Federal do Ceará, Fortaleza, Brazil² Department of Civil Engineering, Post-graduate Program in Civil Engineering: Construction and Infrastructure, Universidade Federal do Rio Grande do Sul (NORIE/UFRGS), Porto Alegre, Brazil³ Key Laboratory of Advanced Civil Engineering Materials of Ministry of Education, School of Materials Science and Engineering, Tongji University, Shanghai, 201804, China⁴ Department of Civil Engineering, Universidade Federal do Ceará, Crateús, Brazil

Abstract: The demand for new alternative sustainable binders has grown in recent years, seeking to reduce the environmental impact embodied in the use of Portland cement-based materials in the construction industry. Alkali-activated materials (AAMs) are a significant focus of investigation because of their capability of lowering CO₂ emissions and the valorization of aluminosilicate wastes. Besides the valorization of wastes, commonly used precursors such as slags and fly ash have their use focused on cement blend production and may have their availability reduced soon, resulting in the need for new materials to be used as precursors in AAMs. Waste clay brick (WCB) is a type of aluminosilicate solid waste material that is recyclable in the construction industry, particularly in AAMs. This review synthesizes current knowledge and insights regarding the application of WCB in AAM manufacturing. It underscores the necessity for further research on engineering properties, including rheology and reaction kinetics, to enhance our understanding of WCB-based AAMs. Additionally, this review aims to provide a comprehensive overview of the existing literature and guide future investigations in this emerging field.

Keywords: waste clay brick, alkali-activated materials, geopolymers, fresh properties, hardened properties, microstructure

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1. Introduction

Concrete is the most widely consumed construction material globally, with Portland cement (PC) serving as the primary raw material for various concrete types^[1,2]. The production of

PC contributes significantly to global CO₂ emissions, accounting for 7%–9% of the total, which reached 3.3 billion tons in 2023^[3,4]. In light of these facts, there is a growing demand for low-carbon binders as alternatives to PC^[5,6]. Alkali-activated

*Correspondence to I. C. Carvalho, ivodecastro1@gmail.com

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materials (AAMs) are emerging as high-potential candidates and are considered a feasible and promising alternative to PC^[3,4,7]. Often called eco-efficient and sustainable cements, AAMs valorize various types of aluminosilicate solid waste and can reduce CO₂ emissions by 50%–80% during production^[8,9].

AAMs and their concretes can have properties equivalent to PC pastes and concretes and are even better in harsh environments^[10,11]. Despite this, problems related to workability and consistency are usually declared, depending on the type and dose of solid precursor and activator used^[12–14]. AAMs are produced by mixing a solid precursor (such as slags, calcined clays, fly ash, rice husk ash, or waste clay brick) with an alkaline solution known as an activator. This process releases aluminate and silicate monomers, which undergo rearrangement and polymerization to enhance the microstructural network of these binders^[8,9,15–18]. Within this category, geopolymers represent a sub-group of AAMs that utilize low-calcium precursors and this subgroup was first introduced by Joseph Davidovits^[19].

The primary products of alkali-activation process are sodium/potassium-aluminosilicate-hydrate gel (N/K-A-S-H) and calcium-aluminosilicate-hydrate gel (C-A-S-H)^[20,21]. These gels are crucial for enhancing network formation and mechanical properties in the hardened state. The predominance of each gel type is determined by the calcium content and the activator used. A higher Ca/Al ratio promotes greater formation of C-A-S-H and affects the coexistence of C-A-S-H and N/K-A-S-H gels, resulting in the formation of the hybrid C-(N/K)-A-S-H gel^[3,22,23].

The precursors used in AAMs (i.e., solid aluminosilicate source) are predominantly derived from waste or by-products generated by various industries, which underscores the sustainability of these alternative binders. The most extensively studied precursors in the literature are blast furnace slag (BFS)^[24–26] and fly ash^[26–29], which comprise a significant portion of the alkali-activated mixtures investigated. However, other waste materials are also being explored as precursors for AAMs, with waste clay brick (WCB) emerging as a promising candidate.

Approximately 1.3 trillion bricks are produced annually, amounting to about 2.85 billion tons^[30]. It is estimated that 30% of this production results in waste, leading to the generation of approximately 860 million tons of WCB each year^[30,31]. WCB can arise from various processes, including breakage during manufacturing due to mishandling and material discarding during quality control. Additionally, WCB is produced during masonry and demolition activities, where it is classified as construction and demolition waste (CDW), along with concrete, gypsum, wood, and metals. On average, WCB constitutes about 30% (by mass) of total CDW, with some regions reporting levels as high as 60%^[32,33]. In this context, the annual generation of WCB as CDW could reach up to 3 billion tons, according to a recent study reported by Chen et al.^[34].

Utilizing CDW in RAMs necessitates a thorough analysis of the chemical composition, given the high heterogeneity of

such waste. Nevertheless, WCB stands out as the most promising CDW for use in AAMs^[35]. Currently, much of the WCB is improperly disposed of in places like slopes and highways, leading to significant social and environmental issues related to pollution^[30,31,35,36]. Research has indicated that WCB can serve as a supplementary cementitious material (SCM), highlighting its potential for contributing to more sustainable construction practices^[34,35,37,38]. In turn, besides numerous studies exploring the use of WCB as a pozzolanic material, recent research has investigated its feasibility as a precursor in AAMs. This interest arises from WCB's composition, which is predominantly comprised of aluminosilicates, along with its semi-crystalline structure resulting from the thermal processes employed in the production of red clay bricks^[39,40].

Most research utilizes materials such as blast furnace slag^[13,14,24–26] and fly ash^[3,41–43] as precursors, which are already established in the cement industry. However, their availability is becoming increasingly restricted in many countries. Scrivener et al.^[44] noted that slag constitutes only 5% of total clinker production, and its typical substitution rate is around 70%. Additionally, fly ash is reported to have a higher availability (30% of clinker production). However, its variable quality, scarcity in certain regions, and limited suitability as SCMs and precursors constrain its use. Given this context, while the availability of these materials is not an immediate issue, it may become problematic in the near future. Consequently, there is a significant focus on researching new materials to serve as SCMs and precursors.

Considering this context, the high availability of WCB and its accessibility from demolition sites, construction sites, and factories make it a promising alternative as a solid aluminosilicate source for AAMs. While there have been reviews published on the use of WCB as a supplementary cementitious material^[35,39], its application in AAMs is still not well understood and necessitates further experimental and review studies to deepen our knowledge on the topic.

This paper aims to provide a comprehensive state-of-the-art review regarding the use of WCB in AAMs. We will discuss the physical and chemical properties of WCB and present an overview of the properties of WCB-based AAMs that have been studied to date. This review seeks to support future research efforts by enhancing understanding of the potential applications and avenues for investigation regarding WCB in AAMs. It is important to note that this review focuses exclusively on waste from clay-based bricks, excluding those produced from other raw materials, such as cement.

2. WCB generation and physicochemical properties

Red clay brick is derived from a non-metallic mineral with significant economic impact, serving as a widely used material in the construction industry and directly supporting numerous jobs and sales in this sector^[45]. In Brazil, a country of vast dimensions, there are over 6900 red ceramic industries that generate approximately 293000 direct jobs^[46]. In 2017, Brazil produced around 15.2 million tons of WCB, much of which

was improperly disposed of in landfills, slopes, and highways^[47,48]. India, one of the world's leading producers of clay bricks, generates approximately 30% of its daily production as waste^[48]. Additionally, Gaibor et al.^[49] report that one-third of total brick production in Europe is discarded as waste, contributing to millions of tons of calcined clay in landfills^[45,47,49]. The geographical distribution of brick production is illustrated in Fig. 1, which highlights the nine leading clay brick-producing countries. Notably, Asia accounts for over 80% of global brick production annually, making it the continent with the highest generation of WCB.

The production process of red clay bricks primarily involves using clay and water as the main raw materials, with

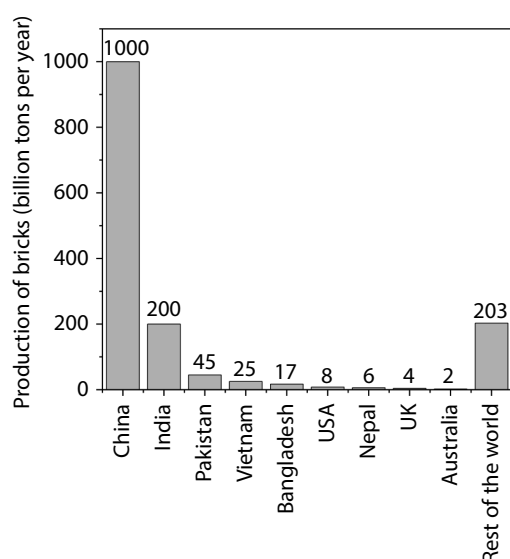


Fig. 1. Brick production rate worldwide, 2018. Reproduced with permission from Ref. [50].

certain types of sand utilized in some processes^[51,52]. This combination is used to manufacture various bricks and blocks^[53–56], following a series of steps that include mixing, extrusion into the desired shape, and firing, which typically occurs at temperatures ranging from 900 °C to 1100 °C. The firing stage is crucial, as it facilitates the physical and chemical transformations necessary to achieve the desired properties of the final product, including strength, low water absorption, good adhesion to coatings, and thermal and acoustic insulation^[53,57,58]. Fig. 2 presents a schematic diagram illustrating the production process of red clay bricks, along with the generation of WCB. Additionally, the transformation of WCB into a fine format (<150 µm) is represented in the illustration, which typically involves processes of collection, grinding, and sieving.

Considering the brick production, most industries need to be modernized because they are often managed in an old-fashioned manner, advancing very slowly in implementing new technologies and knowledge in production. Thus, the generation of waste from production is significant, and the inadequate disposal of this type of waste may generate several socio-environmental problems^[49,59].

From the same perspective of brick production, this process primarily relies on natural gas as its energy source, with approximately 90% of total energy consumption derived from natural gas and the remaining 10% from electricity^[60]. According to Turner and Collins^[61], the energy consumption for brick production is around 540 MJ per ton, which represents about 10% of the energy required to produce one ton of Portland cement^[62,63]. Additionally, life cycle assessment (LCA) studies have investigated the CO₂ emissions associated with the ceramic and brick industry. Quinteiro et al.^[53] and Furszyfer Del Rio et al.^[60] report an emission rate of approximately 0.25 kg of CO₂ per kg of brick. Based on this figure,

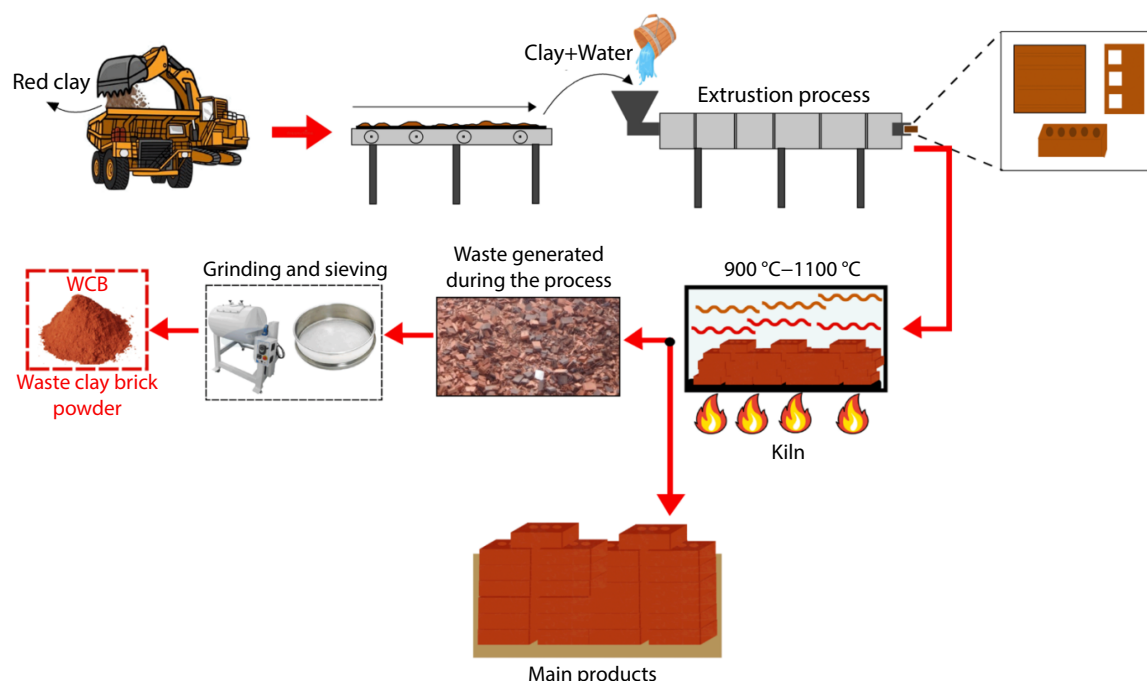


Fig. 2. Schematic diagram of the production process of red clay brick and its waste generated.

the industry is estimated to contribute roughly 27 million tons of CO₂ annually^[53,60–63]. Despite these significant emissions, the red ceramic industry accounts for only 20% of the total CO₂ emissions compared to those of the cement industry^[62,63].

The potential use of WCB as a precursor in AAMs or as SCMs has been studied. Its chemical composition, primarily consisting of aluminosilicate-rich amorphous phases, serves as a key justification for its utilization^[35,64–66]. Table 1 summarizes the chemical composition of WCB as reported by various researchers. This composition can vary based on factors such as the origin of the bricks, firing temperature, and the type of clay used as the raw material. Despite these variations, silica consistently is the most abundant component, comprising between 50% and 70% of the total composition. Aluminum oxide is also present in significant amounts, typically ranging from 12% to 35.5%. This composition based on silica and alumina indicates a good potential for use in AAMs since it is similar to the composition commonly used. Alkali-acti-

vated mixture precursors generally comprise a three-dimensional polymeric chain of Si–O–Al bonds^[19,67,68].

Fig. 3 summarizes key physical and chemical characteristics of WCB particles. It includes the micromorphology of WCB as observed through scanning electron microscopy (SEM) in Fig. 3a, the crystalline structure analyzed via X-ray diffraction (XRD) in Fig. 3b, and a comparison of the chemical compositions of well-established precursors alongside WCB in Fig. 3c, based on reported literature values.

Fig. 3a shows the micromorphology of WCB particles, which can be irregularly shaped, slightly angular, and sharp-edged^[75,76]. The XRD pattern of WCB in Fig. 3b reveals well-defined crystalline phases due to its semi-crystalline nature^[40,77]. The prominent peaks in the XRD pattern correspond to quartz, with a sharp peak at approximately $2\theta = 26^\circ$ ^[78,79]. In Fig. 3c, it is evident that WCB and fly ash exhibit similar chemical compositions, both featuring high SiO₂ contents (50% to 60%), reasonable amounts of Al₂O₃ (15% to 25%), and low calcium content (2% to 10%). Fly ash is exten-

Table 1. Chemical composition of WCB used in various studies.

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	TiO ₂	Na ₂ O	SO ₃	LOI	Ref.
72.2	16.2	6.29	0.22	0.82	2.12	0.96	0.10	-	1.17	[35]
55.32	35.5	5.27	0.19	-	1.28	1.09	-	1.23	-	[65]
63.13	14.15	8.26	4.89	1.03	1.37	1.17	1.09	2.35	2.07	[69]
49.9	16.6	6.5	9.7	5.5	4.4	0.8	0.5	3.3	2.4	[64]
58.13	14.15	13.26	4.89	1.03	1.37	1.17	1.04	2.6	2.23	[70]
58.79	23.98	8.76	0.72	-	1.75	2.28	-	0.98	2.44	[71]
51.7	18.2	6.1	6.1	2.4	4.6	0.8	0.2	-	-	[72]
63.4	12.0	11.0	-	1.6	6.2	1.5	-	-	1.7	[73]
63.89	25.49	7.73	0.29	0.04	0.95	-	-	-	-	[74]

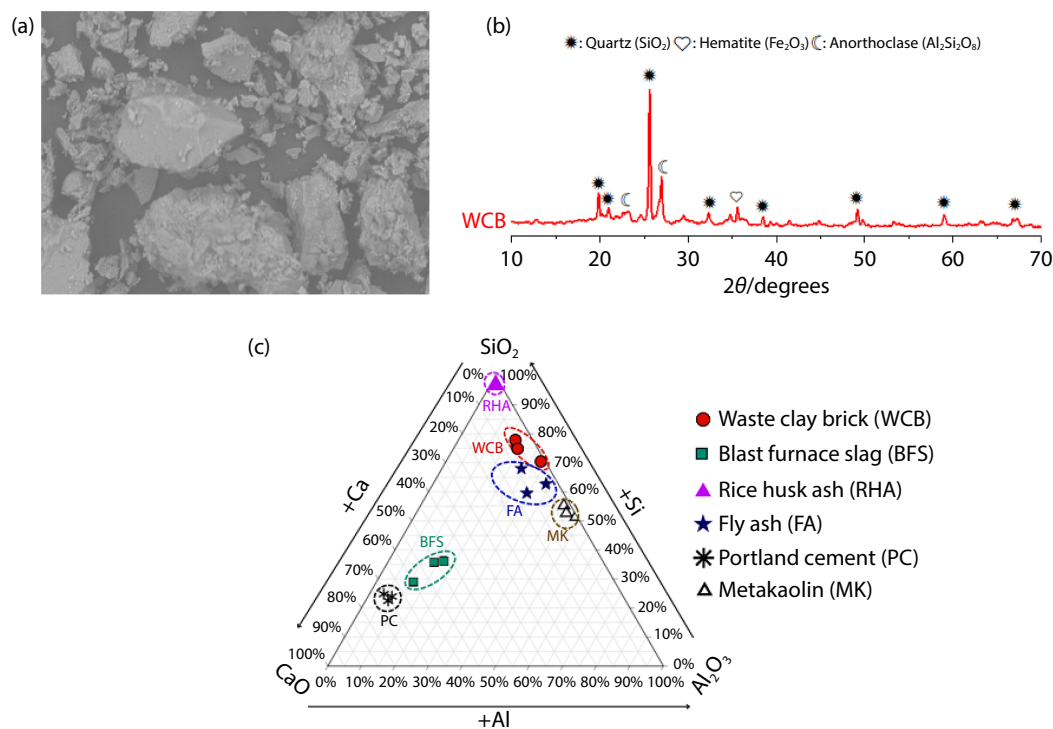


Fig. 3. (a) SEM image, (b) XRD patterns of WCB, and (c) a ternary graph of the chemical compositions of precursors widely used in AAMs. BFS^[41,42,84], RHA^[85–87], FA^[88–90], MK^[91–93], PC^[94–96], and WCB^[65,69,71].

sively utilized in alkali-activated materials^[80–83], and the chemical similarities between fly ash and WCB strongly suggest the potential of WCB as an effective alkali-activated precursor.

The physical properties of particle size, density, and specific surface area are fundamental for evaluating the potential of using WCB as a precursor in AAMs^[97,98]. Smaller particle sizes increase the surface area, enhancing the material's reactivity and its potential for use as a precursor or supplementary cementitious material (SCM)^[4,99–101]. The physical properties of WCB, reported in various studies, are summarized in Table 2. Notably, the density of WCB varies between 2620 and 2710 kg m⁻³, with specific surface area results ranging from 540 to 6485 m² kg⁻¹.

Table 2. Physical properties of WCB used in various studies.

Density (kg m ⁻³)	Blaine specific surface area (m ² kg ⁻¹)	Particle size (μm)	Ref.
2660	540	63	[102]
-	1680	8.8	[77]
2660–2710	-	6–18	[103]
2640	-	<150	[104]
2660	6485	39	[105]
2620	-	10	[106]

3. WCB as an alkali-activated precursor

The worldwide demand to mitigate the environmental impacts of waste and the large-scale production of PC has led to the growth of studies on new alternative binders. Thus, the study of AAMs has grown significantly in recent years, but the use of WCB as a precursor still needs to be addressed in the literature.

This section examines the key properties and parameters of alkali-activated mixtures that incorporate WCB as a precursor. To gain insight into the current status of WCB utilization in AAMs, a comprehensive search was conducted using the Web of Science, Scopus, and ScienceDirect databases. The search utilized the keywords "red ceramic waste" OR "red clay brick" OR "waste clay brick" in combination with "alkali-activated" OR "geopolymer." After applying a filtering process, the search yielded 31 papers published in peer-reviewed journals, which were thoroughly investigated to provide critical information for this review.

3.1. Activation and mix design parameters of WCB-based AAMs

The activation and mix design parameters for alkali-activated mixtures are crucial and are commonly treated as study variables. Understanding these parameters is essential and can serve as a foundation for future research. Table 3 presents the main activation and mix design parameters adopted in the selected studies. This table includes information on the precursors, activators, alkali dosage (%Na₂O), and the silica modulus (SiO₂/Na₂O, Ms). Values not included in the table were not reported in the corresponding papers. Since only sodium-based mixtures were reported, the alkali dosage nomenclature was established as %Na₂O.

This overview underscores the wide predominance of sodium-based activators, with the absence of potassium-based systems being reported. Additionally, significant variations in alkali dosage and silica modulus were observed. Subsequent discussions will focus on values that can optimize the reactivity of WCB-based mixtures.

3.2. Fresh properties of paste and concrete

This section will discuss the main results associated with the fresh-state properties of WCB-based alkali-activated mixtures. The discussions focus on the properties of mini-slump tests that are the indicators of paste's workability, reaction kinetics, setting time, rotational rheology, and oscillatory rheology (i.e., structural build-up) of mixtures.

3.2.1. Mini-slump results

The workability of AAMs is influenced by several factors, particularly precursor particle size, activator type, and the liquid-to-solid or water-to-binder ratio of the mixtures. This property is crucial for alkali-activated binders, as excessively or poorly flowable mixtures can hinder production and render some AAMs impractical^[4]. Additionally, the alkali dosage (%Na₂O) and the silica modulus of the activators significantly affect workability^[4,132]. While this type of analysis is commonly performed in various alkali-activated mixtures^[133–135], it has not been extensively studied in WCB-based AAMs. Workability assessments for AAMs are typically conducted through single-point tests (application of a single shear), determining the spread or slump of the mixtures. Direct comparison of workability between alkali-activated pastes, mortars, or concrete is challenging due to the presence of aggregates.

Some researchers have explored the influence of WCB on the workability properties of AAMs. Zhang et al.^[79] reported results for mixtures of blast furnace slag (BFS) and WCB, indicating that substituting BFS with up to 30% WCB enhanced the workability of the pastes, with slight variations of up to 1.5% compared to the mixture containing 100% slag. In a similar system, Carvalho et al.^[130] reported a convergent result, where WCB incorporation reduced the flow spread diameter of the pastes. The authors associated this behavior with the porous surface of WCB, reducing the amount of free water that favors the mixture's workability and dispersion.

Shen et al.^[109] and Tuyan et al.^[123] also analyzed the workability of alkali-activated pastes and mortars, respectively, using WCB as the sole precursor, investigating the impact of alkali dosage on the flowability of the pastes. The silica modulus for the analysis was set at 1.6, with water-to-binder ratios of 0.3^[109] and 0.45^[123]. Shen et al.^[109] observed, as shown in Fig. 4, that higher %Na₂O resulted in greater spreads in WCB-based AAMs for alkali dosages up to 6%. However, flowability slightly decreased when increasing the dosage from 6% to 8% (%Na₂O), suggesting an optimal alkali dosage around 7% for workability. In the mortars studied by Tuyan et al.^[123], the analysis covered alkali dosages ranging from 4% to 10%, with increased workability noted for all increments of %Na₂O.

The results indicate a lack of consensus regarding the effect of WCB incorporation on the workability of alkali-activated mixtures. Additionally, the influence of activation parameters—such as alkali dosage and silica modulus—on the

Table 3. Activation and mix design parameters of WCB-based alkali-activated mixtures reported.

Ref.	Year	Precursors	Activators	%Na ₂ O	Ms
[47]	2023	WCB + CL*	NaOH	0 to 5.5	Not specified
[107]	2013	WCB + PS*	NaOH + Na ₂ SiO ₃	6 to 9	1.12 to 2.13
[108]	2018	Only WCB	NaOH + Na ₂ SiO ₃	Not specified	1.4
[109]	2022	Only WCB	NaOH + Na ₂ SiO ₃	2 to 8	1.6
[110]	2020	Only WCB	NaOH + Na ₂ SiO ₃	Not specified	0 to 2.2
[111]	2015	WCB + BFS	Na ₂ CO ₃ + Na ₂ SiO ₃	5	1.5
[112]	2016	WCB + PC	NaOH + Na ₂ SiO ₃	2 to 10	1.3
[79]	2021	WCB + BFS	NaOH + Na ₂ SiO ₃	4	1.2
[113]	2022	Only WCB	NaOH + Na ₂ SiO ₃	2 to 8	1.6
[76]	2019	WCB + BFS + FA	NaOH + Na ₂ SiO ₃	5.5	1.1
[114]	2018	WCB + MK	NaOH + Na ₂ SiO ₃	Not specified	1.4
[75]	2023	WCB + CCS* + SF*	NaOH	Not specified	0
[115]	2021	WCB + MK	NaOH + Na ₂ SiO ₃	Not specified	Not specified
[116]	2013	Only WCB	NaOH + Na ₂ SiO ₃	2.5 to 10	0 to 2.0
[117]	2021	Only WCB	NaOH	7.36 to 13.98	0
[118]	2018	WCB + TMW*	NaOH + Na ₂ SiO ₃	Not specified	Not specified
[119]	2017	WCB + PC	NaOH + Na ₂ SiO ₃	2 to 10	Not specified
[120]	2017	Only WCB	NaOH + Na ₂ SiO ₃	4.5 to 5	1.16
[121]	2021	WCB + SG*	NaOH	Not specified	0
[122]	2023	WCB + SCSA*	NaOH + Na ₂ SiO ₃	8.3	1.3
[62]	2022	WCB + CW* + CWW*	NaOH + Na ₂ SiO ₃	0.61 to 1.6	6.39 to 11.06
[123]	2018	Only WCB	NaOH + Na ₂ SiO ₃	4 to 10	0 to 2.2
[124]	2022	WCB + CCS* + SF*	NaOH	Not specified	0
[125]	2017	WCB + PC	Na ₂ CO ₃ + Na ₂ SiO ₃ + NaOH + Na ₂ SO ₄	8	Not specified
[126]	2024	WCB + BFS + FA	NaOH + Na ₂ SiO ₃	Not specified	Not specified
[127]	2024	FA + WCB and BFS + WCB	NaOH + Na ₂ SiO ₃	Not specified	Not specified
[77]	2019	WCB + BFS + FA	NaOH + Na ₂ SiO ₃	Not specified	Not specified
[128]	2017	WCB + FA	NaOH + Na ₂ SiO ₃	Not specified	Not specified
[129]	2024	WCB + Steel slag + FA	NaOH + Na ₂ SiO ₃	Not specified	Not specified
[130]	2024	WCB+BFS	NaOH + Na ₂ SiO ₃	7	1.0 to 1.3
[131]	2024	WCB+BFS	NaOH + Na ₂ SiO ₃	7	1.0 to 1.3

*CL = Carbide lime; CCS = Calcium carbide slag; CW = Concrete waste; CWW = Ceramic wall waste; SF = Silica fume; SG = Silica gel; SCSA = Sugar cane straw ash; PG = Phosphogypsum; PS = Porcelain stoneware; TMW = Tungsten mining waste.

workability of WCB-based pastes remains poorly understood. In these cases, other factors, including the physical and chemical properties of the raw materials, may significantly alter the expected behavior. Furthermore, the outcomes are notably unique to the specific system, including the types of precursors, activators, and mix design aspects employed, generally not following a clear and specified tendency.

3.2.2. Setting time

The setting time of AAMs is a critical property to study, as it is essential for their feasibility, particularly in construction applications^[4]. Excessively long or short setting times can render the material impractical^[4,136]. Various issues related to setting time have been identified in several alkali-activated mixtures^[136–138].

Shen et al.^[109] investigated the setting times in AAMs using WCB as the sole precursor, focusing on the impact of alkali dosage on both initial and final setting times. As shown in Fig. 5a, an alkali dosage of 2% resulted in relatively high initial (110 min) and final (118 min) setting times. In contrast,

increasing the alkali dosage to 4% and 6% led to shorter setting times, indicating that a lower alkali dosage does not promote the polycondensation of the alkali-activated mixture effectively. However, as the alkali dosage increased, the setting times decreased significantly, indicating an enhancement in the degree of reaction of the systems. When the alkali dosage was raised from 6% to 8%, the initial setting time increased to 101 min, while the final setting time reached 118 min, which was similar to the measurements obtained at the lowest activation level (%Na₂O = 2%).

Additionally, Rakhimova and Rakhimov^[111] examined the impact of specific surface area (SSA) of the precursors on the setting time of alkali-activated pastes based on BFS and WCB, using an alkali dosage of 5% Na₂O and a silica modulus of 1.5. As shown in Fig. 5b, increasing the SSA from 300 m² kg⁻¹ to 900 m² kg⁻¹ resulted in a reduction of the initial setting time from 35 min to 10 min and the final setting time from 110 min to 28 min, highlighting the significant influence of this physical property. Furthermore, Ahmed et al.^[127] demonstrated that incorporating WCB in a WCB-FA binary system sig-

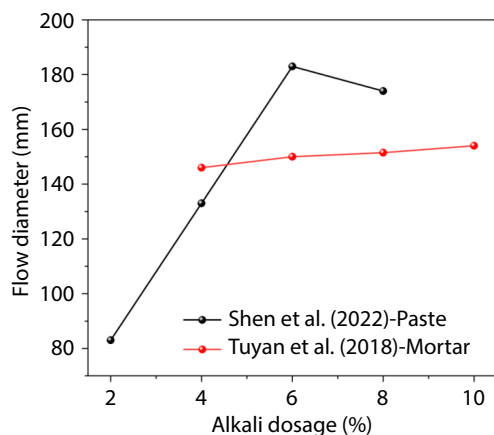


Fig. 4. Influence of alkali dosage (%Na₂O) on the workability of WCB-based AAMs. Adapted from Refs. [109,123].

nificantly reduced setting times, from 780 min (100% FA) to 75 min (100% WCB). This rapid setting was attributed to accelerated reaction kinetics, facilitated by the high-water absorption capacity of WCB particles, which enriched the alkaline solution concentration in the system. Additionally, the higher CaO content in WCB compared to FA promoted enhanced reaction kinetics, further contributing to the reduced setting times. Conversely, in systems combining BFS with WCB, the authors observed an inverse trend, where higher BFS content was correlated with increased rates of alkali activation.

Overall, the effect of WCB incorporation on the setting of alkali-activated mixtures depends on the type of systems involved. In binary systems, the reactivity of the other precursor plays a crucial role, with WCB categorized as a medium-reactivity precursor—ranking above FA and below BFS based on the discussed results. Additionally, identifying the optimized alkali dosage for WCB activation (see Fig. 5a) is essential for guiding future research and explaining certain behaviors observed in these mixtures.

3.2.3. Reaction kinetics

In general, the reaction kinetics of alkali-activated mixtures can be divided into three stages (see Fig. 6)[130]. Stage I, marked by the first heat peak, is associated with the initial dissolution of Si and Al species from the precursors and the release of aluminate and silicate monomers[139]. Stage II represents the polymerization process, indicated by the second exothermic heat peak, which begins at the end of the induction period[140]. Importantly, the appearance of the peak in Stage II does not signify the completion of the dissolution process. Stage III involves the further polycondensation and rearrangement of the networks, typically characterized by a stable reaction period with lower heat release[130]. This analysis is commonly performed using isothermal calorimetry in various studies of AAMs[130,131,139–141].

For AAMs with WCB, Zhang et al.[79] reported that increasing the amount of WCB resulted in a decrease in the heat released during the initial hours of the reaction. This behavior may be linked to a reduced reaction degree in the system when substituting BFS with WCB. Additionally, the authors observed a strong correlation ($R^2 = 0.994$) between WCB content (up to 30%) and the timing of the reaction

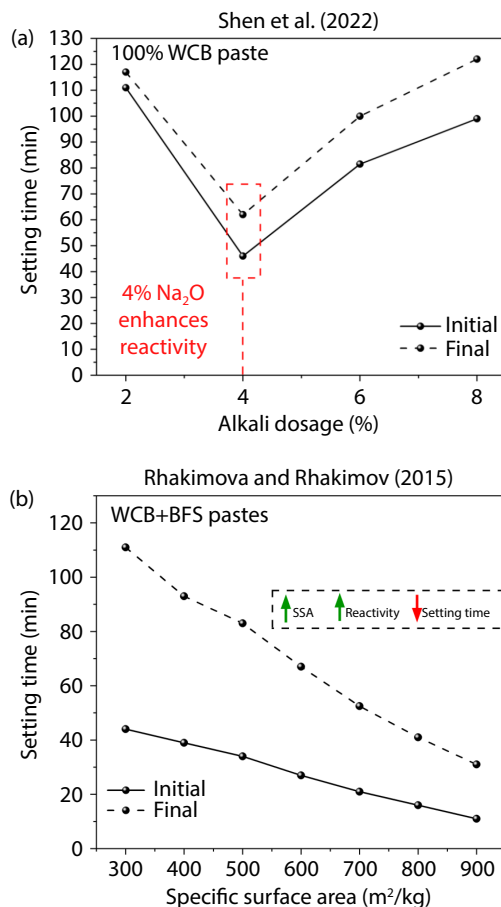


Fig. 5. Influence of (a) alkali dosage (%Na₂O) and (b) specific surface area of precursor on WCB-based AAMs setting times. Adapted from Refs. [109] and [111], respectively.

peak, suggesting that the presence of WCB extended the induction period of the mixtures, indicating it is a less reactive precursor compared to slag. Furthermore, an increase in WCB content led to a decrease in cumulative reaction heat at $t = 72$ h. By $t = 168$ h, the cumulative heat for all mixtures was nearly equal, indicating that reactions were more delayed in pastes containing WCB. The reported data regarding the timing of the reaction peak and cumulative reaction heat for different WCB contents are illustrated in Fig. 7.

A similar behavior was recently observed by Carvalho et al.[130], as shown in Fig. 8, where the incorporation of WCB at levels up to 50% in a slag-based system extended the induction period and resulted in broader heat peaks. A reduction in peak intensity was also noted. The authors attributed this behavior to the differing reactivities of slag and WCB. The lower dissolution of WCB particles results in reduced release of Si and Al monomers, which diminishes the rearrangement of species and the precipitation of aluminosilicate gels. However, the authors also highlighted that substantial incorporation of WCB in a slag system could provide additional nucleation sites, which may facilitate the precipitation of products. Notably, incorporating WCB at 75% completely inhibited the reaction kinetics of the slag-WCB system, as indicated by the isothermal calorimetry curve.

In a one-precursor system, Shen et al.[109] investigated

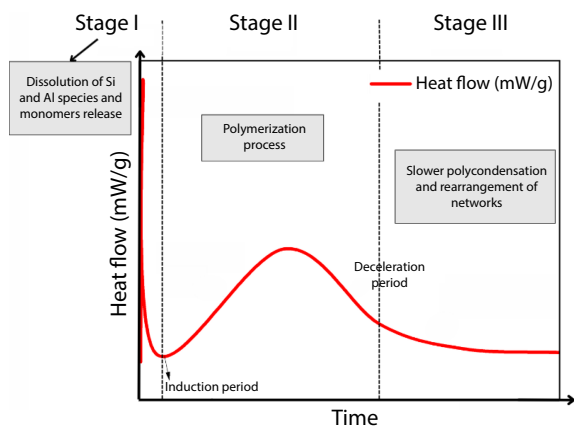


Fig. 6. Isothermal calorimetry graph model for reaction kinetics analysis.

the impact of alkali dosage (%Na₂O) on the reaction of WCB-based alkali-activated pastes. They found that cumulative reaction heat increased with alkali dosages rising from 2% to 6%, indicating an enhanced reaction degree of the mixture. However, at alkali dosages above 6%, a decrease in cumulative reaction heat was observed, attributed to the difficulty in achieving complete dissolution of Si and Al species released by the WCB at higher alkali levels.

Moreover, a study published in 2024^[129] highlighted the beneficial impact of WCB on the initial stages of alkali activation within a ternary WCB - fly ash - steel slag system. The authors suggested that the presence of the anorthoclase phase (as shown in Fig. 3) in WCB could partially facilitate reactions, while the high quartz content may provide additional sites for gel formation, thereby enhancing the dissolution of fly ash.

Considering the discussed scenario, the reaction kinetics of WCB-based AAMs align with expected behaviors given their reactivity potential. When used alongside high-reacti-

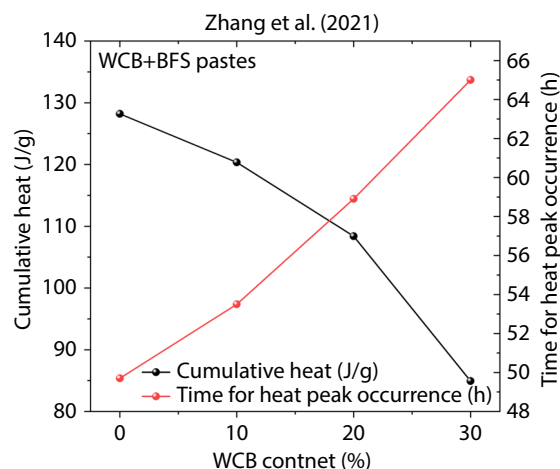


Fig. 7. Influence of WCB incorporation in reaction kinetics of BFS-based AAMs. Adapted from Ref. [79].

vity precursors (such as slags and metakaolin), the incorporation of WCB may be detrimental. In turn, its reaction kinetics indicate that, even on a smaller scale, the dissolution and subsequent product formation occur during the alkaline activation process. Overall, the results associated with this property are well-documented. However, the dissolution/precipitation mechanisms recently explored by Carvalho et al.^[130] require further investigation to deepen the understanding of this material.

3.2.4. Rheology

The rheology study of AAMs is crucial for understanding their behavior in the fresh state. While this analysis has been conducted for mixtures with BFS^[142–144], FA^[145–147], and MK^[148–150], it remains underexplored for mixtures using WCB as a precursor.

Rovnaník et al.^[114] examined the direct impact of WCB on

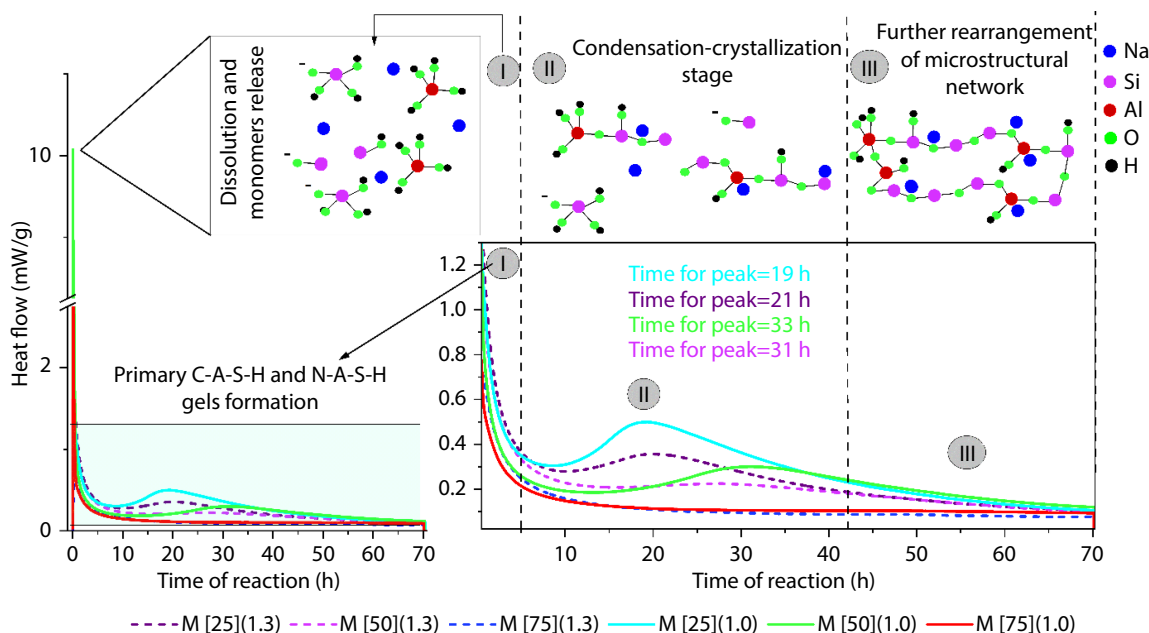


Fig. 8. Isothermal calorimetry curves of slag-WCB AAMs. The M [25] samples represent mixtures with 25% WCB and 75% slag and the same conceptualization was used for all the samples. Reproduced with permission from Ref. [130].

the rheological properties of MK mixtures, finding that higher WCB content reduced the yield stresses at various time intervals (5, 60, 120, 180 min). A similar trend was observed for the plastic viscosity of the pastes, as shown in Fig. 9 for 180 min. The authors noted a Newtonian fluid behavior with increased WCB incorporation, resulting in decreased yield stress. Carvalho et al.^[130] also conducted a rotational rheometry test in a slag-WCB system and measured lower shear stress values for higher WCB content. Additionally, a reduction in both yield stress and viscosity was identified for mixtures with $M_s = 1.0$, while no clear trend was observed for higher M_s value. The authors^[130] also identified the Bingham model as the best model to represent the rheological behavior of the pastes.

The observed behavior in both works^[114,130] may be linked to the reactivity of the co-precursors used. Both slag and MK are known for their higher reactivity, which can contribute to early reactions that rapidly affect the rheology and flow resistance (i.e., viscosity and yield stress) of the pastes. In this context, the incorporation of WCB is associated with a reduction in the overall reactivity of the mixture. Additionally, the physical properties, such as the fineness of the precursors, may influence this behavior in the study by Rovnanik et al.^[114]. However, in the slag-WCB system, this variable was controlled, as the fineness of both precursors was nearly identical^[130].

In another approach, oscillatory rheology was assessed by the same authors^[114,130]. Both works analyzed the mixtures' structural build-up and viscoelastic parameters evolution by measuring the storage modulus (G') and loss modulus (G''), which are responsible for the elastic and viscous behaviors, respectively. This analysis was performed by a small amplitude oscillatory shear test (SAOS) at a frequency of 1 Hz and a strain value (amplitude) of 0.01%.

In the MK-based system, the analysis indicated that the increase in WCB content reduces the structural build-up rate, requiring more time for the loss modulus to exceed the storage modulus^[114]. This crossover point is associated with the material's hardening process. The results indicate that the increase in WCB content hinders the alkali-activation process of the mixtures, as WCB is a less reactive precursor than

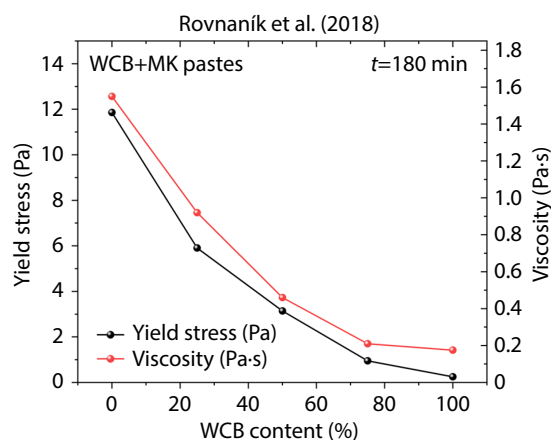


Fig. 9. Influence of WCB content on rheological properties of MK-based alkali-activated pastes. Adapted from Ref. [114].

metakaolin. The structural build-up results identified^[114] are shown in Fig. 10. The mixtures with 0%, 25%, and 50% WCB presented a dominance of the elastic portion (G') since the beginning of the SAOS test, without a turning point.

In more recent work, Carvalho et al.^[130] observed similar behaviors for a slag-based mixture. The incorporation of WCB postponed the occurrence of the crossover point and reduced the storage modulus (G') measurements for up to 120 min. Fig. 11 illustrates the evolution curves of G' (indicated by the pink line), revealing a lower structural build-up rate with larger WCB incorporation. Mixtures with 25% and 50% WCB, represented by samples M[25] and M[50], exhibited similar curves, indicating comparable early-age structural build-up rates despite the incorporation of up to 50%. However, at a WCB incorporation of 75%, this structural build-up rate drastically decreased, aligning with the previously discussed reaction kinetics results in Section 3.2.3.

3.3. Hardened properties of paste and concrete

This section will discuss the main results of hardened state properties, i.e., compressive strength, durability properties, pore structure, and microstructure, of WCB-based alkali-activated mixtures reported in the literature.

3.3.1. Compressive strength

Compressive strength is one of the most studied parameters for AAMs and can be directly influenced by several factors, including curing type, alkali dosage, precursor mix proportions, and silica modulus^[4,127,151]. Alkali-activated mixtures using WCB as a sole precursor have demonstrated high strengths, as noted in previous studies. Fořt et al.^[108] reported compressive strengths of up to 42 MPa at 28 d with WCB mixtures, employing activation parameters of $M_s = 1.4$ and a liquid-to-solid ratio of 0.54. In this study, the authors examined the influence of the mass ratio between the activa-

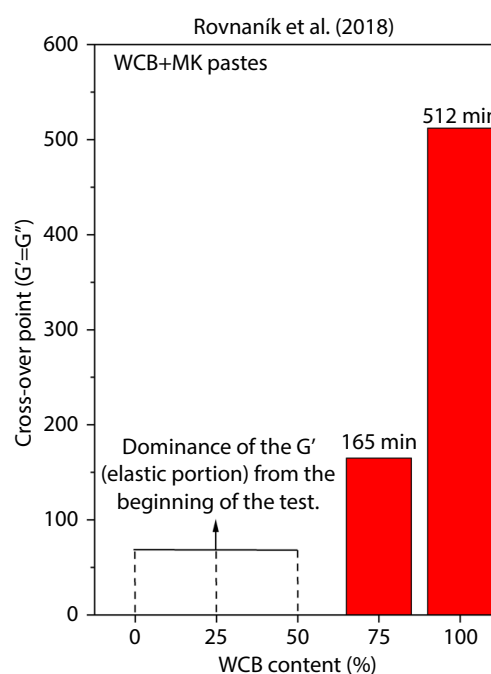


Fig. 10. Impact of the WCB content on the crossover point ($G' = G''$) of MK-based alkali-activated pastes. Adapted from Ref. [114].

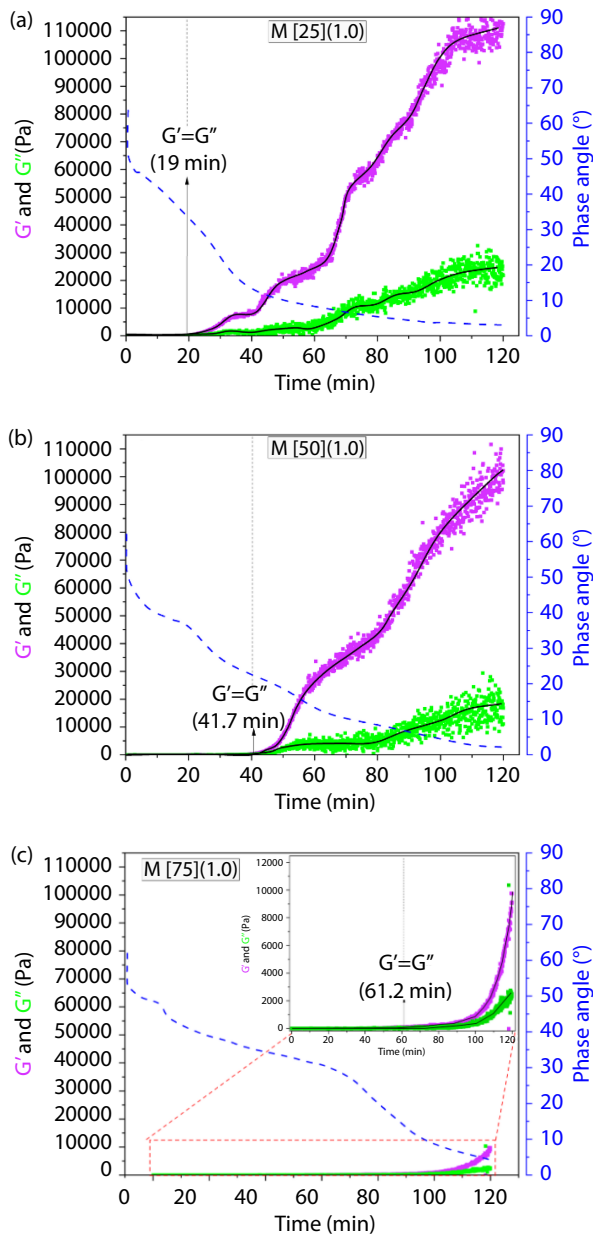


Fig. 11. Viscoelastic parameters evolution as a function of time. The samples M [25] represent mixtures with 25% WCB and 75% slag and the same conceptualization was used for all the samples. Reproduced with permission from Ref. [130].

tors $\text{Na}_2\text{SiO}_3/\text{NaOH}$ (SS/SH) for low-concentration NaOH solutions and found that an increasing SS/SH ratio negatively impacted the compressive strength.

Hwang et al.^[77] identified a negative impact of WCB in alkali-activated slag pastes, as shown in the compressive strengths obtained at four different ages in Fig. 12. This behavior is closely linked to the differences in chemical composition between the two precursors: BFS contains high CaO content, promoting the formation of C-S-H and C-A-S-H gels, which enhance mechanical strength. Additionally, the authors noted that the semi-crystalline nature of WCB impedes the complete dissolution of particles during the alkali activation reaction, resulting in a less dense microstructure and reduced compressive strength of the pastes^[77]. This

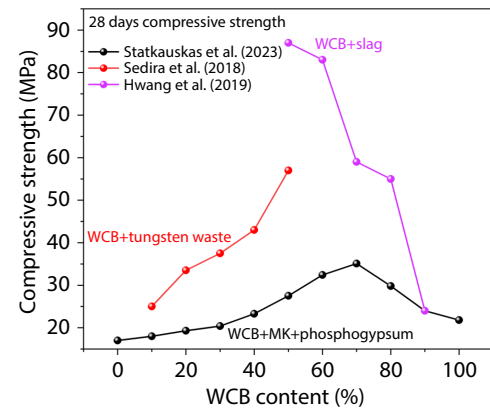


Fig. 12. Influence of WCB content on compressive strength of various pastes. Adapted from Refs. [75,76,118].

tendency converges with a recent report from Carvalho et al.^[131] where compressive strength values ranging from 50.45 MPa to 68.68 MPa in WCB contents up to 50% were identified.

Statkauskas et al.^[75] investigated alkali-activated pastes using varying proportions of MK and WCB, along with the addition of 5% phosphogypsum. The compressive strengths determined from these mixtures, illustrated in Fig. 12, showed an enhancement with increasing WCB content up to 70%, which was identified as the optimal value. Beyond this level, a significant decrease in strength was observed. This behavior was attributed to the high presence of active silica and aluminum, which can cause microcracks in the paste, negatively impacting compressive strength. Another hypothesis suggested that, at higher WCB contents, there might be insufficient alkaline solution available to react with the WCB fully.

Compressive strength was a key focus in the study by Sedira et al.^[118], which investigated alkali-activated blends utilizing WCB and tungsten mining waste as precursors. As illustrated in Fig. 12, varying the WCB content between 10% and 50% resulted in a notable increase in compressive strength at both 7d and 28 d, with a remarkable 136% enhancement observed at 28 d. Similarly, Ahmed et al.^[127] evaluated the compressive strength at 28 d in a FA-WCB system. Their findings indicated that compressive strength initially increased with WCB content, reaching an optimal level of around 40%, before declining with further increases in WCB. This trend aligns with results reported by Mahmoodi et al.^[62].

In a one-precursor mixture, Li et al.^[113] investigated the influence of alkali dosage on the compressive strength of WCB-based alkali-activated pastes. Their results, presented for two curing ages (3 d and 28 d) with Na_2O contents ranging from 2% to 8% (see Fig. 13), revealed that low alkali dosages (e.g., 2%) were inadequate for reacting with WCB, leading to low strength values. However, an increase in alkali dosage to 6% resulted in enhanced compressive strength due to improved reactivity. Conversely, a further increase to 8% resulted in a decline in mechanical performance.

Additionally, Reig et al.^[116] explored the impact of alkali dosage (ranging from 5% to 9% Na_2O) on the compressive strength of alkali-activated mixtures made from WCB, as depicted in Fig. 13. The analysis indicated a positive correlation between alkali dosage and compressive strength for con-

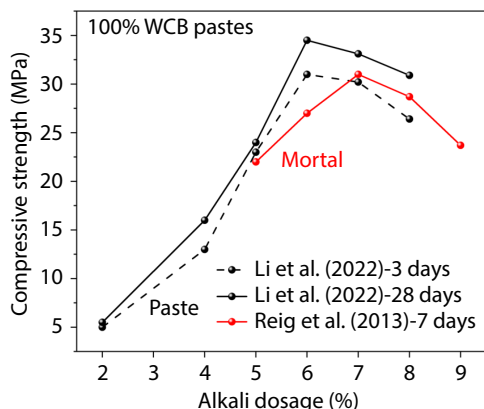


Fig. 13. Impact of alkali dosage (%Na₂O) on the compressive strength of WCB-based alkali-activated mixtures. Adapted from Refs. [113,116].

tents up to 7% Na₂O at 7 d. Beyond this threshold, a decrease in strength was observed, corroborating the findings of Li et al. [113].

The results presented highlight the variability in compressive strength observed in WCB-based mixtures. It is evident that incorporating WCB in AAMs can yield satisfactory mechanical performance. However, achieving optimal compressive strength is influenced by several critical factors beyond just the presence of WCB. Key parameters such as mix design, alkali dosage, water-to-binder ratio, and the types of precursors used play a significant role in determining the material's properties. The discrepancies in observed strength results can be attributed to these variations in formulation and conditions. Ultimately, the main conclusion regarding the utilization of WCB is its feasibility in alkali-activated mixtures to achieve satisfactory strength, along with the identification of an optimized alkali dosage that enhances mechanical performance.

3.3.2. Durability

The durability properties of WCB-based AAMs remain largely underexplored. Notably, only one study (Zhang et al. [79]) has specifically investigated these properties, assessing the impact of sulfuric acid exposure on WCB-blast furnace slag (BFS) mixtures. The authors found a weakening intensity of the vibration peaks of the Si–O–T band (where T represents tetrahedral Si or Al) in samples subjected to sulfuric acid, indicating the susceptibility of these chemical bonds to acid attack. Additionally, there was a marked increase in the decomposition of the calcium-aluminosilicate hydrate (C-A-S-H) gel under acidic conditions. X-ray diffraction (XRD) tests revealed the formation of gypsum (CaSO₄ · 2H₂O) phases, particularly at elevated calcium levels in the system.

The study also noted that replacing BFS with WCB resulted in a reduction in the resistivity of the mixtures, a critical factor for evaluating corrosion potential in concrete. Furthermore, the diffusion of chloride ions—a primary contributor to reinforcement corrosion—was found to increase with higher WCB content. This phenomenon is attributed to the lower reactivity of WCB particles compared to BFS, leading to a more porous microstructure that facilitates ion diffusion. Overall, these findings underscore the need for further

research into the durability characteristics of WCB-based AAMs to better understand their long-term performance and resilience in various environmental conditions.

3.3.3. Pore structure

Mercury intrusion porosimetry (MIP) is commonly used to characterize the pore structure in AAMs. This pore structure is closely related to the gels formed during the geopolymerization process, where even small variations in precursor or activator parameters can significantly affect product formation and, consequently, the pore characteristics [84,152]. In materials with high calcium content, the predominant gel produced is calcium-aluminosilicate hydrate (C-A-S-H), which is associated with an increased amount of bound water in the system. This characteristic enhances the pore-filling capacity of the material [84,153].

The impact of incorporating WCB into alkali-activated mixtures on pore structure was explored by Guo et al. [128] in a FA-based geopolymer. The study involved substituting up to 30% of FA with WCB while keeping other variables constant. By comparing the pore structure of the 100% FA blend to that of the 70% FA and 30% WCB blend, the research aimed to elucidate the effects of WCB on the porosity and overall performance of the geopolymer. The study conducted by Guo et al. [128] revealed significant changes in the pore structure of mixtures incorporating WCB. Specifically, the incorporation of 30% WCB resulted in a decrease in the average pore diameter from 13.7 nm to 10.1 nm and a reduction in the maximum pore diameter from 73.6 nm to 12.7 nm. Additionally, the porosity factor decreased from 15.3% to 12.6%. The analysis further indicated that the volumes of larger pores (ranging from 20–50 nm, 50–200 nm, and >200 nm) were reduced. Notably, an increase in pore volume was observed only for pores smaller than 20 nm, suggesting that the incorporation of WCB leads to a refinement of the pore structure, enhancing the material's density and potentially its durability.

Another investigation by Fořt et al. [108] focused on the effect of alkali dosage in an alkali-activated paste composed entirely of WCB. The results indicated that higher levels of Na₂O correlated with an increase in the volume of large pores (>100 nm). However, the total porosity percentage showed little variation, suggesting that the alkali dosage primarily influenced the distribution of pore sizes rather than the overall porosity.

Additionally, the porosity of a fly ash-blast furnace slag-WCB alkali-activated system was examined [126]. Visual assessments (see Fig. 14) revealed that the inclusion of WCB reduced the presence of macropores in the mixture. This reduction is attributed to the filling of larger pores by reaction products generated in the presence of WCB particles that can be linked to the nucleation sites role of WCB particles [130], leading to a denser microstructure overall.

Fig. 15 illustrates the influence of WCB content on the porosity and compressive strength of a ternary fly ash-blast furnace slag-WCB alkali-activated mortar. The authors [126] found that incorporating WCB significantly reduced the total porosity of the mixture, optimizing its pore structure. Specifically, a 40% WCB content led to a 44% decrease in total porosity.

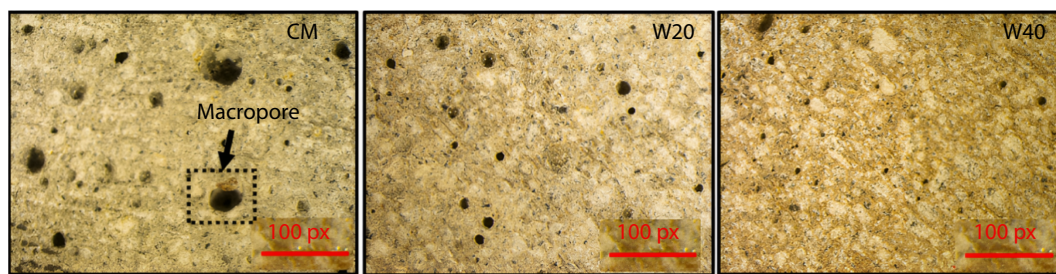


Fig. 14. Porosity surface investigation of FA-BFS-WCB alkali-activated pastes (CM = 0% WCB, W20 = 20% WCB, W40 = 40% WCB. Reproduced with permission from Ref. [126].

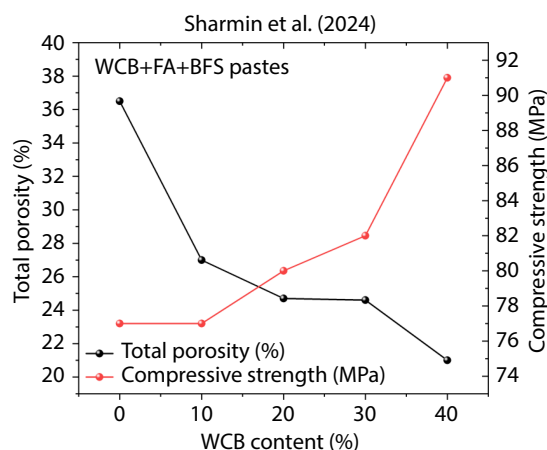


Fig. 15. Porosity and compressive strength of FA-BFS-WCB alkali-activated pastes. Adapted from Ref. [126].

Notably, this incorporation also resulted in a substantial reduction in the volume of micropores (<320 nm). Consequently, the improved pore structure contributed to an increase in compressive strength, with the mortars achieving over 90 MPa for the 40% WCB mixture.

3.3.4. Microstructure

Shen et al.^[109] investigated the microstructural characteristics of AAMs using WCB as the sole precursor, employing Fourier-transform infrared spectroscopy (FTIR) to assess the impact of alkali dosage ranging from 2% to 8% Na₂O. The study revealed that increasing the alkali dosage to 6% resulted in a decrease in the intensity of the Si–O–Si stretching vibration band while simultaneously increasing the intensity of the Si–O–T stretching vibration band (where T represents tetrahedral Si or Al). This shift indicates an enhancement in the formation of network structures, which correlates with improved mechanical performance due to the greater formation of aluminosilicate gels associated with the Si–O–T band. However, when the alkali dosage was raised to 8%, a reversal in this trend occurred: the intensity of the Si–O–Si stretching vibration bands increased, while the intensity of the Si–O–T stretching vibration bands decreased. The authors attributed this behavior to the excessive alkali dosage, which hinders the formation of three-dimensional Si–O–T structures and negatively impacts the dissolution rate during the alkali-activation process. Key band assignments relevant to WCB-based AAMs are summarized in Table 4.

The FTIR analysis confirms the feasibility of using WCB as a precursor in AAMs. Key bands associated with alkaline activa-

tion, such as the Si–O–T band, are present in all samples, indicating that the fundamental structural characteristics are preserved throughout the process. This consistent behavior supports the effectiveness of WCB in AAM formulations.

The microstructure of alkali-activated mixtures is often further characterized using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS). Robayo-Salazar et al.^[125] investigated the effects of incorporating Portland cement into WCB-based alkali-activated pastes. The results of this analysis are illustrated in Fig. 16. The microstructure of alkali-activated pastes using 100% WCB reveals the formation of sodium aluminosilicate hydrate (N-A-S-H) gels, attributed to the high content of SiO₂ and Al₂O₃, coupled with the near-zero CaO content (0.73%) in WCB particles. According to Robayo-Salazar et al.^[125], the incorporation of 10% Portland cement significantly enhances the formation of portlandite (calcium hydroxide) as observed in the SEM/EDS analysis at EDS points 5–7.

The presence of portlandite ensures the availability and saturation of Ca²⁺ ions within the system, leading to a structural transformation of the N-A-S-H gels formed during the dissolution of WCB particles and the alkali-activation process. This transformation results in the formation of a hybrid gel, termed (N, C)-A-S-H, as indicated at EDS points 8–11. The co-existence of C-A-S-H and N-A-S-H gels, along with the hybrid gel, contributes to the enhanced mechanical performance of the mixtures.

For comparison, Fig. 17 presents SEM/EDS evaluations of cementitious mixtures incorporating WCB as a supplementary cementitious material (SCM) at 0%, 20% and 40% replacement levels of Portland cement^[154]. These analyses highlight the microstructural changes and interactions between WCB and the cement matrix, illustrating the impact of varying WCB content on the formation of hydration products and overall microstructure. Mixtures containing 0% and 20% WCB exhibited a denser, less porous microstructure with minimal micro-cracking. In contrast, the micrographs of pastes with 40% WCB revealed a more heterogeneous and less dense morphology. The paste with 20% WCB displayed partially hydrated WCB particles (EDS points 3 and 5) and indicated the formation of C-A-S-H gel (EDS points 1, 2, and 4) as a result of the pozzolanic reaction between WCB and portlandite. For pastes with 40% WCB, an almost pure C-S-H gel was identified (EDS point 8), with WCB particles encased in C-S-H gels, alongside the presence of C-A-S-H (EDS points 6, 7, 9, and 10).

In contrast, the microstructures of alkali-activated mix-

Table 4. FTIR bands reported for WCB-based AAMs.

Bands	Wavenumber (cm ⁻¹)					
	Ref. [109]	Ref. [123]	Ref. [79]	Ref. [75]	Ref. [76]	Ref. [118]
Stretching and bending vibration of O–H	3250–3650	3500–4000	3392	3453	3450	3650
Asymmetric stretching vibration of O–C–O	1630	1410–1484	1465	1452	1423	1450
Asymmetric stretching vibration of Si–O–T (T = Tetrahedral Si or Al)	1458	1000	997–938	999	1011	970
Stretching vibration of Al–O	1086	-	-	-	-	1054
Symmetric stretching vibration of Si–O–Si	780	526–530	670–661	722	-	-
Deformation vibration of Si–O–Al	694	537	-	-	-	694

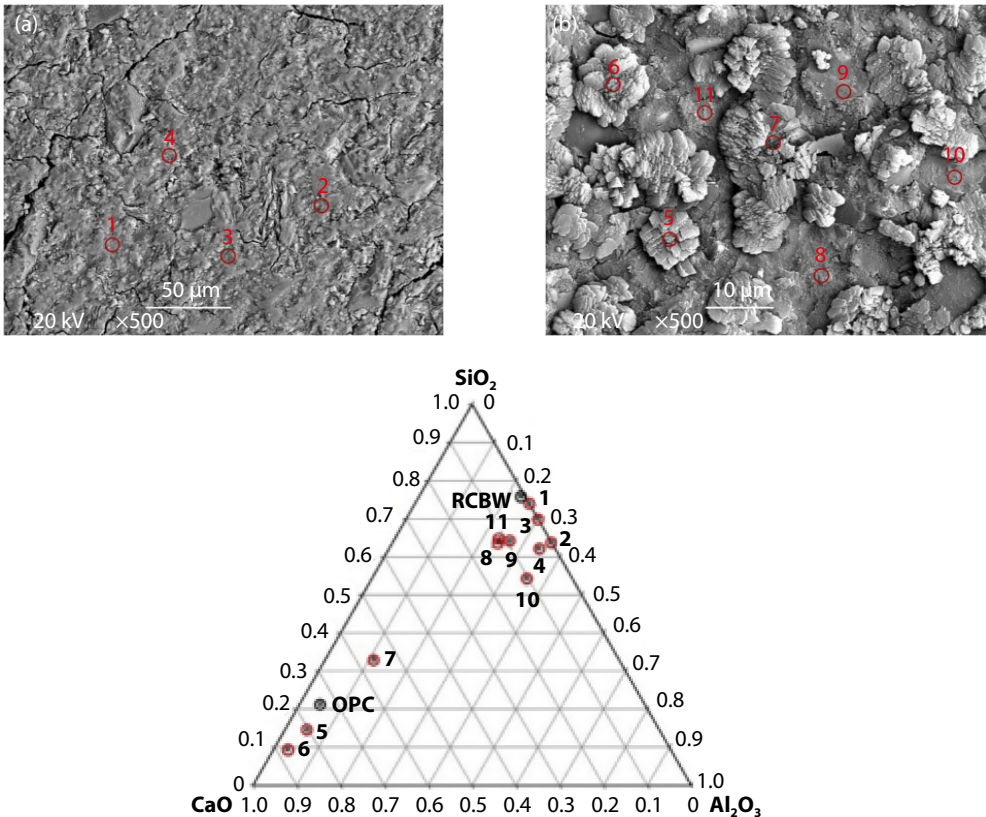


Fig. 16. SEM/EDS investigation of alkali-activated pastes: (a) 100% WCB and (b) WCB + 10% OPC. Reproduced with permission from Ref. [125].

tures^[125] predominantly formed C-A-S-H gels only when Portland cement was incorporated, given the low CaO content in WCB. In these mixtures, the N-A-S-H gel was the primary product of the reactions. However, when WCB was utilized as a supplementary cementitious material (SCM)^[154], the hydration of cement led to the formation of C-S-H gels, while the pozzolanic activity of WCB contributed to the development of C-A-S-H gels.

3.4. Environmental impacts

In the literature, the evaluation of CO₂ emissions and energy consumption in the production of AAMs is typically conducted through Life Cycle Assessment (LCA). This methodology allows researchers to quantify the CO₂ emitted and the energy utilized throughout the materials and processes involved in producing these mixtures. Despite a few studies^[155–157], large-scale analyses of this type for alkali-activated mixtures remain limited.

Some reports specifically focus on alkali-activated mix-

tures utilizing WCB as a precursor. Liang et al.^[158] investigated the environmental impact of mixtures composed of blast furnace slag, fly ash, and WCB, examining how replacing FA with WCB affects CO₂ emissions and energy consumption through an LCA framework. The findings indicated that increasing the WCB content, up to a maximum of 40%, led to substantial reductions in both CO₂ emissions and energy consumption. Specifically, emissions decreased from 191 kg CO₂ ton⁻¹ and 2755 MJ ton⁻¹ (0% WCB) to 57.4 kg CO₂ ton⁻¹ and 1241.1 MJ ton⁻¹ (40% WCB). Similarly, Carvalho et al.^[131] reported reductions of up to 65% in CO₂ emissions and 75% in energy consumption when comparing binary alkali-activated mixtures (slag-WCB system) with Portland cement systems. These studies underscore the environmental benefits associated with using WCB in alkali-activated materials, highlighting its potential as a low-carbon alternative in construction applications.

Li et al.^[113] further explored the environmental implica-

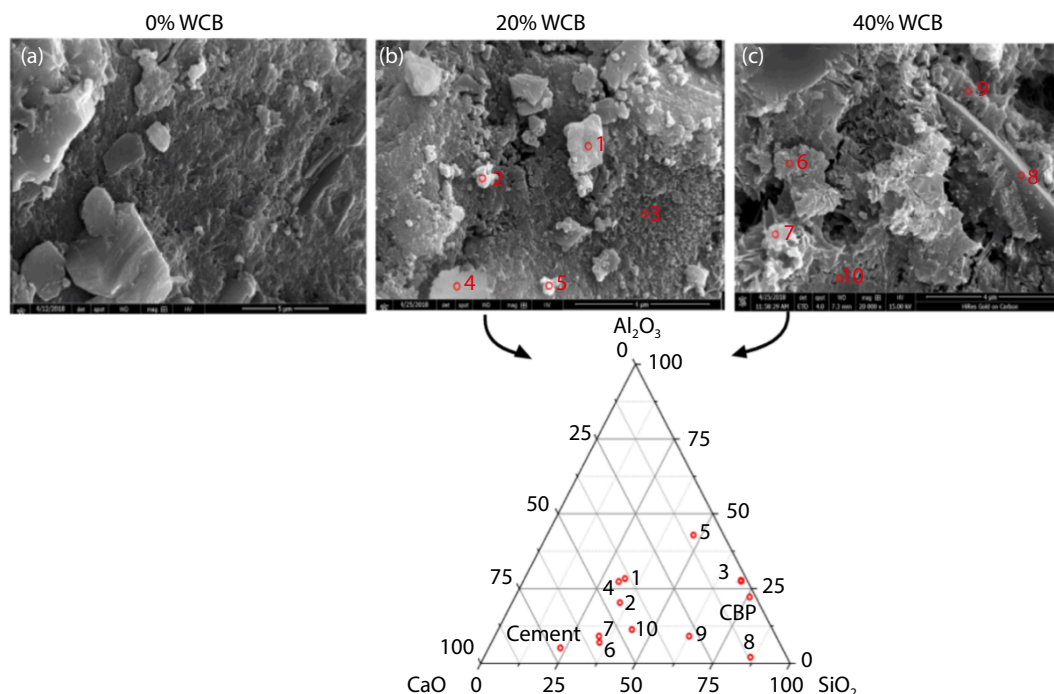


Fig. 17. SEM/EDS investigation of Portland cement pastes with 0%, 20% and 40% of WCB incorporation at 90 d of curing. Reproduced with permission from Ref. [154].

tions of alkali dosage in pastes made with 100% WCB. Their results, illustrated in Fig. 18, showed that increasing the quantity of alkaline activators also heightened CO_2 emissions and energy consumption. This increase is primarily attributed to the production processes of sodium hydroxide and sodium silicate, which contribute significantly to overall emissions and energy costs [113,131,159]. Notably, a significant difference was observed in CO_2 emissions between alkali-activated blends and conventional Portland cement blends, underscoring the environmental benefits of WCB-based AAMs as potential eco-friendly binders. However, for an alkali dosage of 8%, the energy consumption of the AAMs exceeded that of the PC binder by 200 MJ m^{-3} , highlighting the considerable energy demands associated with the production of alkaline activators [63,113,159].

4. Current status and future perspectives of the theme

The main factors related to studies of WCB-based alkali-activated mixtures are associated with the precursors and activators used, the variables studied, and the tests and analyses proposed. Based on this, Table 5 exposes the status of these factors and their subtopics concerning the knowledge already existing in the literature (well known or needing further investigation). The sub-types shown in Table 5 refer to the main parameters of each factor listed, aiming to cover various parameters that can be changed in the design of an experimental study.

This section aims to help identify research gaps that can be explored in future works, broaden the diversity of analyses related to the topic, and increase the knowledge regarding WCB-based alkali-activated mixtures.

The combination of WCB with another type of precursor is considered well-known in the literature due to the diversity of combinations already investigated. Furthermore, a fair number of articles are already studying the use of WCB as a single precursor. Binary mixtures have been studied widely, but ternary combinations using WCB as a precursor have yet to be discussed in the literature.

There was a complete dominance of studies using sodium-based activation regarding the activation method. In contrast, no studies based on other types of activation, such as potassium-based activation, were identified in this review. Such variation in the activation process could provide different behavior and further investigations are necessary.

A wide variety of properties have been studied in WCB-based materials. Despite this, in most cases, more than replication of these analyses has been required to establish knowledge of these properties in this type of material. Mechanical and microstructural properties stand out as analyses that have been carried out extensively and already have much information in the literature. On the other hand, assessments of rheology, reaction kinetics, pore structure/porosity, setting time, durability, and environmental impacts still need to be further investigated to consolidate them in the literature.

5. Conclusions

AAMs are a great sustainable alternative to reduce the negative environmental impacts of conventional binders. The significant reduction in CO_2 emissions and the use of waste that does not have an adequate destination corroborate this sustainable characteristic. One of these residues that can be used is WCB, which is widely generated globally without a defined destination.

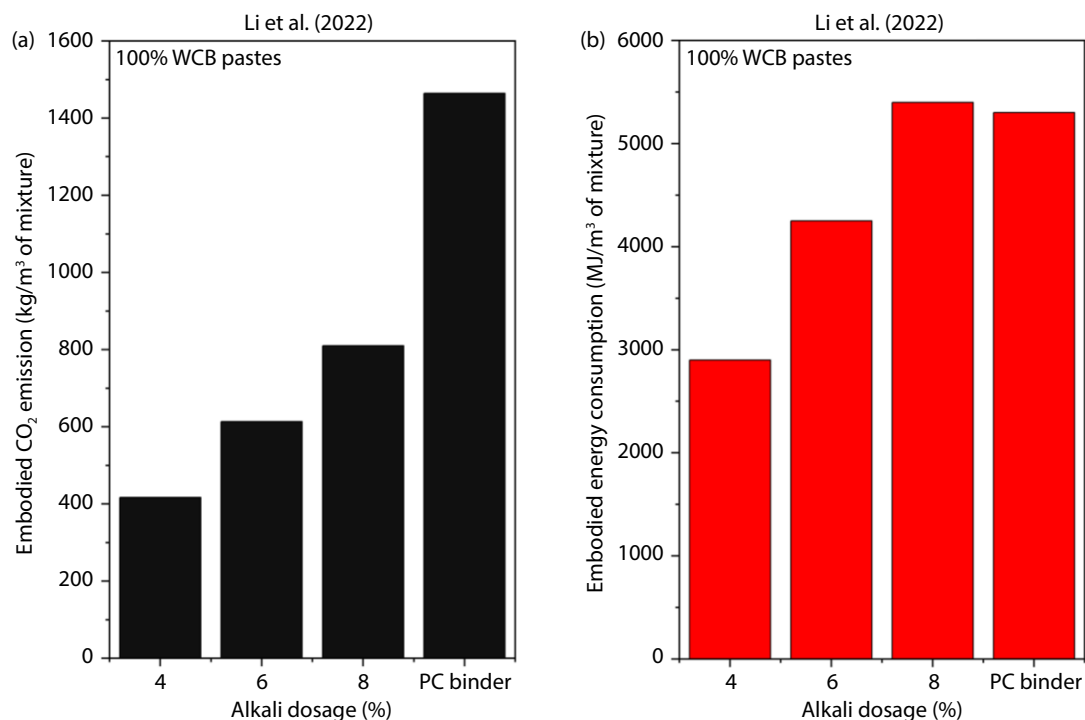


Fig. 18. Impact of alkali dosage on environmental performance of WCB-based AAMs. Adapted from Ref. [113].

Table 5. Main factors linked to the study of WCB-based alkali-activated mixtures.

Type	Sub-type	Status
Precursors	Combination with another precursor	Well known
	Utilization as a sole precursor	Well known
	Binary systems	Well known
	Ternary systems	Needs further investigation
Activators	Sodium-based	Well known
	Potassium-based	Needs further investigation
	Silica modulus (Ms)	Needs further investigation
	Alkali dosage	Well known
Variables	Curing temperature and type	Well known
	Liquid-to-solid or water-to-binder ratio	Needs further investigation
	Precursors mix proportion	Well known
Properties and analysis	Rheology	Needs further investigation
	Reaction kinetics	Needs further investigation
	Pore structure	Needs further investigation
	Mechanical performance	Well known
Variables?	Setting time	Needs further investigation
	Environmental impact	Needs further investigation
	Microstructure	Well known
	Durability	Needs further investigation

Incorporating WCB as a precursor in alkali-activated mixtures has demonstrated satisfactory results, confirming its potential for this application. However, there remain significant gaps in the understanding of this topic that warrant further investigation. A primary area for future research is the elucidation of the reaction mechanisms of WCB particles in alkaline solutions. The material's complex and varied chemical composition, along with its crystalline structure, suggests that the mechanisms of reaction are not straightforward. A deeper analysis in this area could enhance our understand-

ing of the observed behaviors and contribute to the existing state of knowledge.

Additionally, it is important to provide insights regarding the role of WCB particles as nucleation sites. Despite their relatively lower reactivity, WCB may be impactful in alkali-activated binders and its use in binary and ternary systems presents promising opportunities for waste management and the development of low-carbon cement alternatives. Such mechanism is important to be further addressed using novel technologies and techniques.

Author contribution statement

Ivo de Castro Carvalho: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft. **Zuhua Zhang:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Ana P. Kirchheim:** Writing – review & editing, Visualization, Methodology, Conceptualization, Supervision. **Heloina N. Costa:** Writing – review & editing, Methodology, Conceptualization, Supervision, Project administration. **Antônio E.B. Cabral:** Writing – review & editing, Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

Zuhua Zhang is a Co-Editor-in-Chief and Ana P. Kirchheim is an Editorial Board Member for *Materials Reports: Solidwaste and Ecomaterials*, and they were not involved in the editorial review or the decision to publish this article. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ivo de Castro Carvalho is a Ph.D. student at the Universidade Federal do Rio Grande do Sul. He earned his bachelor's degree in 2022 and his master's degree in 2024 from the Universidade Federal do Ceará, Brazil. He began his PhD program in 2024, focusing his research on the development of low-carbon binders, rheology of cementitious and alkali-activated materials, and advancements in clinker reactivity and mineralogy.