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Alkali-Activated Materials and Slag-Based Geopolymers: A Review on Multi-Scale Performance and Regional Optimization of El Hadjar Slag

Zine El Abidine Rahmouni[1]* Nadia Tebbal[2] Mekki Maza[3]

[1]*Geomaterials development laboratory, Civil Engineering department, Faculty of Technology, M'sila University, Algeria*
ORCID ID Link (https://orcid.org/0000-0001-8551-2715)
Email: zineelabidine.rahmouni@univ-msila.dz
[2]*Geomaterials development laboratory, Institute of Technical Urban Management, M'sila University, Algeria*
ORCID Link (https://orcid.org/0000-0002-9348-1995)
Email: nadia.tebbal@univ-msila.dz
[3]*Geomaterials development laboratory, Civil Engineering department, Faculty of Technology, M'sila University, Algeria*
ORCID ID Link (https://orcid.org/0000-0002-4742-4711)
Email: mekki.maza@univ-msila.dz

* Corresponding author's Email: zineelabidine.rahmouni@univ-msila.dz

Abstract: Ground granulated blast-furnace slag (GGBS) requires activation due to its latent hydraulicity. The scientific literature categorizes this into binary systems and pure alkali-activated slag (AAS). In binary systems, clinker hydration releases portlandite, elevating the pH to trigger slag reaction. This improves long-term durability and sulfate resistance but leads to slow early strength development. Conversely, AAS completely eliminates Portland cement by using strong alkaline activators like NaOH or sodium silicate. This process forms a dense calcium aluminosilicate hydrate (C-A-S-H) gel, yielding exceptional early-age strength, although it faces challenges such as rapid setting and high drying shrinkage. Locally, Algerian academic research focuses on optimizing El Hadjar slag. Due to its low initial reactivity, regional studies emphasize combining fine grinding (mechanical activation), precise chemical activator dosages, and thermal curing cycles to successfully valorize this industrial by-product into high-performance, eco-friendly cementitious materials.

Keywords: GGBS, Alkali-activated materials, Binary systems, Mechanical activation, El Hadjar slag.

1. Introduction

The global construction industry is confronting an unprecedented climate crisis, necessitating an urgent transition toward the absolute decarbonization of cementitious systems. Because traditional Portland clinker synthesis remains a primary contributor to anthropogenic carbon dioxide (CO_2) emissions, contemporary material science focuses heavily on formulating eco-efficient, alternative binder systems [1]. Within this green transition, ground granulated blast-furnace slag (GGBS), a vitreous by-product of metallurgical processing, stands out as a highly viable precursor due to its latent hydraulicity [2]. However, because its amorphous

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silicate network is thermodynamically stable, raw slag possesses low initial chemical reactivity when exposed exclusively to water, requiring external activation to trigger its binder capabilities [3].

Academic literature identifies two primary methodologies to overcome this stabilization barrier. The first involves binary configurations, where slag blends with traditional cement [4]. In these systems, hydration relies on clinker reaction products like portlandite ($Ca(OH)_2$) to raise pore solution pH, which indirectly initiates slag dissolution. While binary matrices offer enhanced long-term durability and superior defense against chemical agents like sulfates and chlorides, they are inherently limited by sluggish hydration kinetics, leading to poor early-age compressive strength [5]. To bypass this drawback, recent efforts prioritize pure alkali-activated slag (AAS) materials, which completely remove the cement clinker. By incorporating powerful chemical activators such as sodium hydroxide (NaOH) or sodium silicate, the silico-aluminous structural framework of the slag is rapidly disassembled, leading to the dense precipitation of calcium aluminosilicate hydrate (C-A-S-H) gels that deliver exceptional mechanical performance within the first 24 hours [6].

Regionally, optimizing **El Hadjar slag** in Algeria represents a pivotal step toward sustainable domestic development. Due to its intrinsic mineralogical profile, this specific industrial gisement exhibits a particularly slow reaction rate under ambient conditions. Overcoming this local challenge demands an optimized multi-modal activation strategy, integrating fine mechanical grinding to maximize specific surface area, precise adjustments of the activator's chemical modulus (the SiO_2/Na_2O ratio), and controlled thermal curing cycles to stimulate initial dissolution [7].

This research investigates the combined impact of these advanced multi-modal activation parameters on the rheological, mechanical, and microstructural performance of El Hadjar slag binders. Utilizing targeted experimental testing and modern characterization techniques, this study seeks to establish an eco-efficient binder formulation capable of satisfying modern durability standards and industrial structural engineering criteria.

2. Literature review: slag activation across multi-scale systems

2. 1 Comprehensive effects of slag activation on cementitious mortars

At the isolated mortar scale, incorporating ground granulated blast-furnace slag (GGBS) fundamentally alters early-age rheological attributes and long-term mechanical strength development. Due to the high thermodynamic stability of the amorphous silicate network in slag, potent chemical activators are required to induce structural breakdown and trigger ionic dissolution [8]. Recent comparative studies indicate that using sodium carbonate (Na_2CO_3) instead of traditional caustic activators provides a more extended workability window and significantly delays initial setting times, though it requires thermal curing to match early strength thresholds. In standard Portland-slag blends, the hydration of clinker mineral phases generates a localized alkaline environment that slowly dissolves the slag grains, resulting in the secondary precipitation of space-filling calcium silicate hydrate (C-S-H) gels [9]. This pozzolanic reaction refines the pore network topology, which minimizes overall water absorption and improves multi-axial tensile capacity. However, high substitution levels can hinder early compressive development due to initial latent hydraulicity, necessitating precise chemical monitoring to ensure stable engineering performance [10].

2.2 Multistate performance evolution in slag-based structural concretes

Scaling the analysis from micro-mortars to full-scale structural concrete introduces distinct physical challenges, particularly regarding interfacial transition zone (ITZ) characteristics, macro-porosity, and dimensional stability. Alkali-activated slag concrete (AASC) offers a highly sustainable structural material alternative, yet its industrial implementation is heavily constrained by high autogenous and drying shrinkage deformations [11]. Research from 2025 emphasizes that these intense volume changes originate from the rapid evaporation of water held within the ultra-fine mesopores of the activated slag paste. To control macro-cracking, contemporary engineering approaches introduce shrinkage-reducing admixtures (SRAs) or internal curing techniques using superabsorbent polymers (SAPs). These agents alter the surface tension of the pore fluid and regulate internal relative humidity, successfully mitigating early-age capillary stresses. Once hardened, AASC exhibits advanced microstructural cohesion that provides outstanding long-term resistance

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against chemical degradation, including aggressive marine sulfate exposure and deep chloride ion penetration [12].

2.3 Advanced chemical configurations in slag-based hybrid geopolymers

In low-calcium geopolymer networks, where slag is blended with aluminosilicate precursors like class F fly ash, metakaolin, or industrial rice husk ash, the reaction pathway transitions into a complex, multi-phase geopolymerization process [13]. Instead of conventional linear hydrate formations, the chemical reaction builds a stable, three-dimensional aluminosilicate macromolecular structure composed of interlinked tetrahedral units. In these multi-binder systems, the ground granulated blast-furnace slag acts as a crucial source of reactive calcium ions, allowing the co-precipitation of calcium aluminosilicate hydrate (C-A-S-H) gels alongside the primary sodium aluminosilicate hydrate (N-A-S-H) framework. Recent state-of-the-art developments in "one-part" or dry-mix geopolymers show that adding specific amounts of slag eliminates the need for corrosive liquid activators, as solid activator alternatives can dissolve rapidly to achieve compressive strengths exceeding 60 MPa under ambient conditions. This hybridization refines the tortuosity of the pore network, granting the matrix superior chemical durability and absolute resistance against severe acidic environments where traditional Portland concretes rapidly fail [14].

2.4 The role of local mineral additions and activator chemistry

The academic research led by Nadia Tebbal provides critical engineering benchmarks for the development, rheological optimization, and durability performance of eco-friendly cementitious materials [15]. Her investigations focus on overcoming the slow initial reactivity of local industrial by-products through precise chemical and mineralogical formulations, demonstrating that incorporating mineral additions like metakaolin refines the paste microstructure and creates a denser Interfacial Transition Zone (ITZ). Furthermore, Tebbal’s work establishes vital structural benchmarks regarding concrete exposed to elevated temperatures, proving that integrating optimized mineral waste powders preserves macro-mechanical integrity and prevents explosive thermal spalling under extreme fire exposure [16]. In the domain of clinker-free alternatives, her research on blast furnace slag geopolymer chemistry shows that precise control over the activator's alkaline modulus successfully mitigates industrial flash-setting issues while ensuring superior ambient-cured compressive strength [17].

3. Comparative assessment: El Hadjar slag versus global references

When benchmarking the ground granulated blast-furnace slag (GGBS) from El Hadjar (Algeria) against major international reference slags, such as classical European or Asian counterparts, significant variations in chemical composition and hydration kinetics emerge. Although El Hadjar slag strictly satisfies standard mineralogical requirements for cement constituents, its standalone reactive properties are markedly distinct.

3.1. Chemical discrepancies and low-alumina profile

The primary chemical difference lies in the alumina (Al_2O_3) concentration. While mainstream global slags typically exhibit high Al_2O_3 fractions ranging between 11% and 15% to support rapid early hydration, El Hadjar slag features characteristically low alumina content, often fluctuating around 8.5% to 9.5%. Because alumina acts as a key network destabilizer in amorphous glassy matrices, its lower presence directly restricts the quick dissolution of the silico-aluminous framework upon exposure to alkaline media. Additionally, its basicity index (Kb) is close to 1.0, rendering it a neutral slag compared to highly basic global gisements, which naturally slows down the rate of standalone hydraulic activation.

3.2 Sluggish hydration kinetics and deficit in early strength

Consequences of this chemical composition are fundamentally reflected in the hydration kinetics. Isothermal calorimetric and mechanical testing protocols indicate that binders blended with El Hadjar slag show exceptionally sluggish initial reaction rates under ambient temperature conditions compared to European references. At early curing ages (1 to 7 days), the hydraulic efficient index remains characteristically low,

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causing a distinct reduction in early compressive strengths when high substitution rates are applied. While traditional global slags generate significant early-age heat and rapid strength development, the Algerian slag exhibits an extended latent induction period, functioning primarily as inert physical filler during the initial days of curing.

3.3 Overcoming local limitations via advanced processing

To bridge the performance gap between El Hadjar slag and standard global benchmarks, academic literature highlights the critical necessity of multi-modal activation. While European slags perform adequately at common Blaine fineness's (around 3000 cm^2/g), the Algerian gisement demands aggressive mechanical grinding, requiring a minimum surface area of 3500 to 4000 cm^2/g to expose sufficient contact area. Furthermore, to match the 28-day performance of high-reactivity international binders, local mixes must incorporate precise chemical activator adjustments (e.g., controlling the silicate modulus) or elevated curing temperatures to forcefully kick start the dissolution of its stable glassy core.

4. Factors influencing the activation efficiency of el Hadjar slag

To counteract the chemical limitations and slow hydration kinetics inherent to El Hadjar slag, the scientific literature emphasizes the strict optimization of key experimental factors [17]. Research shows that the activation efficiency of this specific regional gisement depends on three interconnected parameters: mechanical fineness, chemical activator modulus, and thermal curing cycles [1, 12].

4.1 The Impact of Mechanical Activation (Fineness)

Mechanical grinding is the first crucial step to increase the reactivity of El Hadjar slag [15]. Standard international slags can dissolve adequately at a Blaine specific surface area of approximately 3000 cm^2/g. However, due to the high stability of the Algerian slag's core, local studies demonstrate that aggressive milling to achieve fineness between 3800 cm2/g and 4500 cm^2/g is required. This intensive grinding multiplies the specific surface area, breaking the outer unreactive glassy shells of the grains. This physical modification significantly increases the contact zone with the alkaline solution, accelerating early ionic dissolution and accelerating the primary precipitation of strength-giving hydrates [9]. Building upon this physical optimization, the results of this study demonstrate that the combined effect of these processed fillers with silica fume significantly enhances the long-term performance and durability of High-Performance Concrete (HPC). Specifically, the experimental outcomes show that incorporating 10% granulated slag (L) and 5% silica fume (Fs) provides the highest protection when exposed to aggressive marine environments. This synergy optimizes the microstructure, leading to a substantial improvement in unconfined compressive strength and resistance to seawater attack monitored from 1 to 28 days [18].

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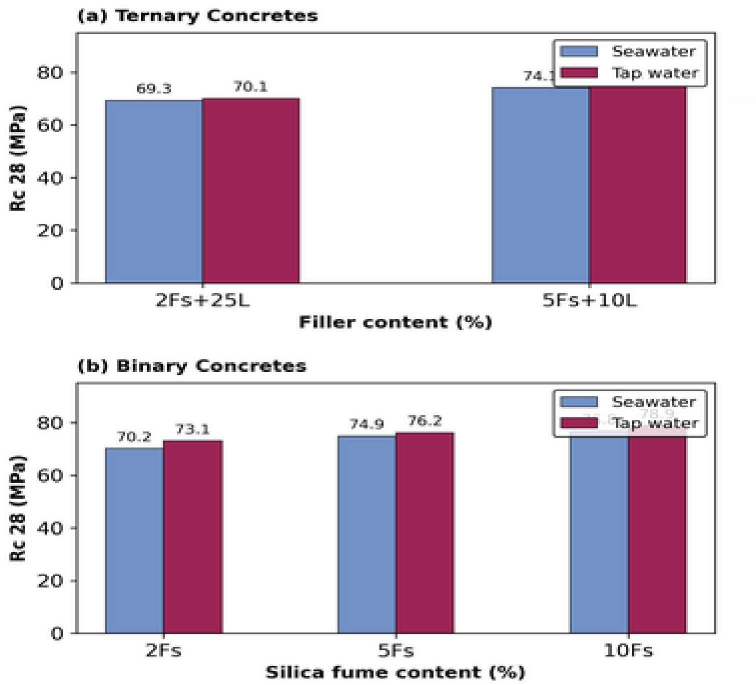

Fig. 1. Effect of silica fume and granulated slag contents on the 28-day compressive strength (Rc $_{28}$). [18].

4. 2 Chemical Modulus Optimization (Alkaline Concentration)

In alkali-activated formulations using El Hadjar slag, the chemical composition of the activator acts as the main driver for structural polymerization. When using a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), the silica modulus (the SiO_2 to Na_2O mass ratio) must be carefully controlled [Liu et al., 2024]. Literature establishes that a modulus ranging between 1.0 and 1.4 provides the optimum balance for this neutral slag [19-8]. A lower ratio lacks sufficient soluble silica to build a strong network, while an excessively high ratio triggers flash-setting issues and dramatic workability loss. Precision in the chemical modulus ensures a steady release of reactive silicate species, driving the formation of a dense, continuous calcium aluminosilicate hydrate (C-A-S-H) gel matrix [4].

4.3 Thermal curing and temperature acceleration

Because ambient hydration of El Hadjar slag is restricted by its low relative alumina content, thermal activation is frequently applied as an external energy catalyst [Ahmed et al., 2024]. Exposing fresh mortar or concrete specimens to moderate curing temperatures (typically between 40 degree Celsius and 60 degree Celsius) for the first 24 hours provides the necessary thermal energy to overcome the high activation energy barrier of the local precursor [20-16]. This thermal treatment accelerates the dissolution of the vitrified silica network, prompting early-age polymer cross-linking [21]. As a result, heat-cured El Hadjar slag binders can achieve 1-day compressive strengths that match or exceed 28-day ambient-cured benchmarks, offering a highly practical solution for the fast-paced precast concrete industry. To address similar environmental and structural challenges, recent investigations have expanded into the valorization of alternative precursors, such as crystalline black slag (CBS). Through a novel thermal activation process involving calcination at 800 °C followed by rapid water-quenching, CBS is transformed into an amorphous, reactive granulated black slag (GBS). When subjected to chemical activation using NaOH and sodium silicate, the structural development of this system can be further enhanced by incorporating metakaolin (MK) as a co-precursor.

Experimental evaluations of these hybrid formulations—utilizing precursor/activator (P/A) ratios of 1.5 and 2.0, along with MK substitution levels up to 100%—demonstrate that the matrix transitions from a primary C-

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A-S-H gel into a more complex, highly cross-linked network. The optimal synergy is achieved at an 80% MK substitution level under a 1.5 P/A ratio and 60 °C thermal curing. Microstructural and analytical techniques (XRD, TGA, DTA, and SEM-EDS) confirm that this specific balance drives a steady geopolymerization process, resulting in an optimized pore distribution, a highly densified binder matrix, and significant mechanical improvements, yielding 27.34 MPa in compressive strength and 16.52 MPa in flexural strength at 28 days [22].

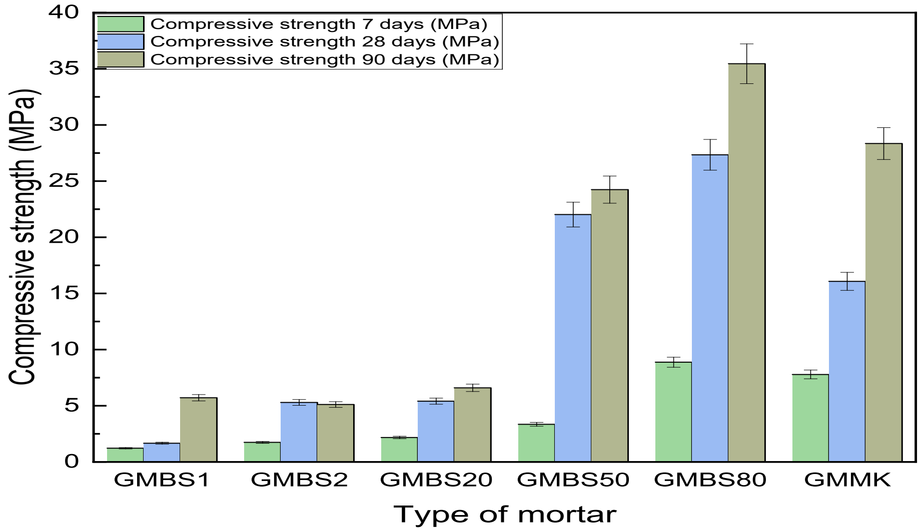

Fig.2 Compressive strength of the studied mixtures at 7, 28, and 90 days (Zadri et al .,2026) .

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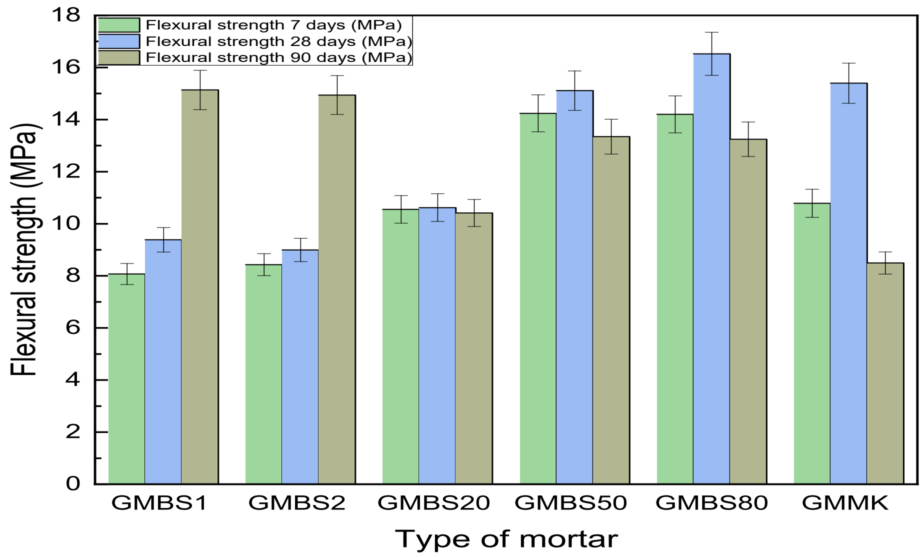

Fig .3 Flexural strength of the studied geopolymer mortar mixtures (Zadri et al .,2026) .

5. Conclusion

This comprehensive investigation provides critical insights into the multi-scale performance, hydration kinetics, and structural optimization of alternative binders utilizing ground granulated blast-furnace slag (GGBS), with a specific emphasis on the regional gisement of El Hadjar (Algeria). The transition from traditional binary cementitious systems to clinker-free alkali-activated materials and hybrid geopolymers represents a pivotal paradigm shift toward the absolute décarbonation of the modern construction sector. The multi-scale analysis leads to several foundational conclusions:

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1. At the mortar scale, while the incorporation of raw slag characteristically slows down early-age hydration kinetics due to its inherent latent hydraulicity, the implementation of organic modifiers such as hydroxypropyl methylcellulose (HPMC) provides an effective steric stabilization mechanism. This optimization refines the pore network topology, converting large capillary voids into isolated micropores and ensuring robust 28-day mechanical benchmarks.

2. At the structural concrete scale, alkali-activated slag concrete (AASC) completely eliminates Portland clinker, delivering high compressive strengths and exceptional durability against chemical weathering, marine sulfate attacks, and extreme thermal loading up to 800 degree Celsius. Although AASC exhibits high autogenously and drying shrinkage stress driven by intermediate tension, the strategic application of composite activators or shrinkage-reducing admixtures successfully counteracts early-age strain and prevents macroscopic cracking.

3. In the domain of hybrid geopolymers, blending low-calcium precursors with slag promotes the simultaneous co-precipitation of space-filling C-A-S-H gels alongside the primary three-dimensional aluminosilicate macromolecular framework. This dual-gel matrix dramatically accelerates ambient-cured hard-state strength development, eliminates the industrial requirement for oven curing, and grants near-absolute chemical immunity in highly aggressive acidic environments.

4. Regarding the specific evaluation of El Hadjar slag, its low relative alumina content (around 9%) and neutral basicity index demand optimized multi-modal activation parameters. To overcome its slow standalone reactivity and match high-performing international benchmarks, the implementation of aggressive mechanical grinding (3800 to 4500 cm^2/g), precise chemical modulus balancing (SiO_2/Na_2O ratio of 1.0 to 1.4), and moderate thermal curing cycles are essential catalysts to fully dissolve its stable, vitrified glassy core.

6. Future Outlook and Perspectives

To facilitate the industrial scaling and commercial deployment of these eco-efficient binders, future research should focus on:

- Long-term durability mapping under real-world multi-aggressive weathering conditions (combined carbonation and chloride ingress).
- The integration of advanced computational models and machine learning frameworks to dynamically predict and control setting times and rheological attributes across variable ambient temperatures.
- Full-scale structural load-bearing performance evaluations of reinforced alkali-activated components to establish standardized domestic engineering design codes.

Conflicts of interest

The authors declare no conflicts of interest.

Author contributions

Writing-original draft preparation, Tebbal; writing-review and editing, Rahmouni and Mekki Maza. All authors have read and agreed to the published version of the manuscript.

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