

Anhydrous Borax in Fly Ash–Slag Geopolymer Concrete: Evidence and a Research Framework

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Abstract

Rapid setting and loss of workability can restrict the use of fly ash–slag geopolymer concrete, particularly when slag is introduced to support strength development under ambient conditions. This narrative review examines the evidence for borate-mediated reaction control and develops a research framework for externally added anhydrous borax. Published studies are compared by precursor composition, activation route, borax hydration state, and the relationship between fresh and hardened properties. The synthesis identifies a recurring possibility of delayed setting, but the associated strength response varies with formulation and age. Evidence obtained with hydrated borax, elevated-temperature fly ash systems, or combined admixtures does not establish a transferable dosage for anhydrous borax in concrete. A staged framework is therefore proposed in which matched paste and mortar screening precede verification across concrete formulations with different target strengths. The base activator and water contents remain fixed, while borax-derived sodium is reported separately. Dosage selection combines a usable placement window, flow retention, stability, and strength requirements; full compressive responses and complementary microstructural measurements then test the consequences of the selected treatment. The framework distinguishes observed retardation from proposed surface inhibition and network modification mechanisms. Its contribution is a traceable route for evaluating a formulation-specific performance window, without presuming an optimum dosage or presenting planned experiments as completed results.

Keywords

Anhydrous Borax; Fly Ash–Slag Geopolymer Concrete; Setting Control; Workability Retention; Research Framework

1. Introduction

Fly ash–slag binders offer a route to concrete based on alkali activation of aluminosilicate precursors. Their practical use depends on achieving a workable placement period together with adequate hardening. In ambient-cured fly ash concrete, Nath and Sarker [1] found that incorporating ground granulated

blast-furnace slag (GGBFS) supported early strength development while shortening setting time and reducing workability in the formulations examined. This trade-off makes reaction control an engineering requirement, especially when mixing, transport, and placement cannot be completed immediately.

The response to a retarding additive depends on the chemical environment into which it is introduced. Activator type affects slag reaction kinetics, hydrate assemblage, and microstructural development [2]. In blended fly ash–slag systems, the chemistry and distribution of binding gels also evolve with precursor ratio and age [3]. Controlled gel studies demonstrate that calcium availability and alkalinity influence the compatibility of sodium aluminosilicate hydrate and calcium aluminosilicate hydrate phases [4]. The term geopolymer concrete is retained here for the blended material, while alkali-activated material is used when discussing the broader literature; the terminology does not imply a single gel structure.

Borax has already been investigated in several alkali-activated systems. The central question is therefore whether existing evidence can support a chemically defined and practically useful external-addition route for anhydrous sodium tetraborate, $\text{Na}_2\text{B}_4\text{O}_7$. The answer requires distinguishing compounds, activators, and performance criteria that are often grouped under the same label. This review develops that comparison and translates it into a staged research framework for fly ash–GGBFS concrete. The proposed contribution is a set of linked decisions connecting dose definition, placement performance, strength development, compressive deformation, and mechanism testing.

2. Review Scope and Evidence Selection

This is a targeted narrative review with a prospective research framework. Searches conducted in September 2026 combined anhydrous borax, sodium tetraborate, borax hydrate, fly ash, slag, alkali activation, setting, workability, strength, and microstructure. Publisher pages and institutional repositories were used to check bibliographic details and accessible experimental descriptions. Primary studies were selected for direct relevance to borate additions or for a specific role in interpreting blended-binder chemistry, compressive response, or specimen preparation.

The comparison records whether the borax hydration state and activation route could be verified. Where only an abstract or partial text was accessible, the synthesis is restricted to the reported qualitative finding. Studies involving other precursors or additional admixtures provide contextual evidence, rather than interchangeable measurements. Heterogeneous dosage bases and testing conditions preclude pooled effect sizes. The proposed experiments in Section 4 are a research agenda; no new experimental dataset is reported.

3. Borate Addition and the Limits of Evidence Transfer

3.1. Compound Identity and Activation Route

Anhydrous, pentahydrate, and decahydrate sodium tetraborate contain different amounts of tetraborate per unit mass. Equal mass percentages therefore supply different boron and sodium quantities, and hydrated forms also introduce crystallization water. Boric acid is a further distinct case because it supplies no sodium. Comparisons should identify the chemical formula, purity, dosage denominator, water accounting, and addition procedure before assigning a common treatment category.

Liu et al. [5] examined anhydrous borax combined with sodium hydroxide to activate Class F fly ash under elevated-temperature conditions relevant to well cementing. Setting was delayed, with hardening also affected. Li et al. [6], in contrast, investigated decahydrate borax in alkali-activated slag and reported delayed setting with a different mechanical response in their test series. These findings support the feasibility of borate-mediated reaction control, but they do not isolate hydration state: precursor composition, activator chemistry, and temperature differ simultaneously.

Table 1 compares directly relevant studies without ranking their dosage recommendations. The distinctions determine what can be carried into a framework for externally added anhydrous borax.

Table 1. Relevant borax studies and limits of transfer to the proposed anhydrous external-addition route. FA, fly ash; APTES, aminopropyltriethoxysilane.

Study and system	Verified borax form	Evidence and transfer limit
Liu et al. [5] Class F fly ash	Anhydrous	Delayed setting at elevated temperatures; not ambient FA-GGBFS concrete.
Li et al. [6] Activated slag	Decahydrate	Delayed setting with a favorable mechanical response in that series; different hydrate and precursor.
Yousefi Oderji et al. [7] One-part FA/slag	Hydrate not verified	Workability and strength changed with age; full methods needed for chemical dose comparison.
Hanani et al. [8] Ambient FA/GGBFS concrete	Pentahydrate	Setting delay in matched mixtures; dissolved-addition history differs from dry anhydrous addition.
Tran et al. [9] One-part printable FA/slag	Pentahydrate	Open time and early strength affected; printing criteria and dose denominator differ.
Yu et al. [10] FA/slag with APTES	Hydrate not verified	Combined admixtures delayed setting and moderated strength loss; not evidence for borax alone.

The closest precursor match is not necessarily the closest processing match. Hanani et al. [8] used pentahydrate borax dissolved during activator preparation, whereas the present framework specifies anhydrous powder addition with unchanged base activator quantities. Similarly, the open-time measurements of Tran et al. [9] concern one-part printable mixtures. Those results motivate time-dependent testing but do not define acceptance thresholds for conventionally placed concrete.

3.2. Setting Delay and Mechanical Performance

Setting delay, initial flow, and flow retention measure different aspects of fresh behavior. A mixture may resist penetration for longer while still losing its ability to spread or consolidate. Conversely, an initially fluid mixture may be unsuitable if it segregates or cannot develop the required early strength. A retarder should consequently be assessed against a placement window and hardening requirements, rather than judged from initial setting time alone.

The reviewed mechanical responses are formulation dependent. In one-part fly ash-slag binders, Yousefi Oderji et al. [7] reported an early-age compressive-strength penalty followed by improved later-age strength in the investigated system. Li et al. [6] reported preserved compressive strength and improved flexural strength for decahydrate borax in their slag-based series. These outcomes cannot be reduced to a universal statement that borax either improves or weakens alkali-activated binders. They instead identify age and composition as necessary comparison dimensions.

Recent work also limits claims about borax acting alone. Yu et al. [10] investigated sodium tetraborate together with aminopropyltriethoxysilane in fly ash-slag geopolymer. Their reported mitigation of the borax-associated strength penalty concerns the combined treatment. It supports investigating interactions between admixtures, but it does not establish a strength benefit for anhydrous borax as the sole added component. A formulation-specific performance window must therefore be demonstrated through matched controls.

3.3. Mechanisms That Require Discrimination

Two recurring interpretations concern interference with early surface reactions and changes in subsequent network formation. Li et al. [6] proposed a borate- and calcium-containing surface barrier in their slag system. Wang et al. [11] interpreted retardation in lithium-slag geopolymer in terms of changes involving boron-containing bonds after sodium tetraborate was introduced into the activator. Lithium slag is chemically distinct from GGBFS, and this activation procedure differs from dry external addition.

These interpretations provide testable alternatives. A surface-controlled process would require evidence linking additive location and early precursor reaction to delayed heat evolution and setting. A network-modification explanation would require structural evidence for the chemical environment of boron and its evolution during hardening. Changes in sodium supply, solution chemistry, and additive dissolution may contribute concurrently. Holding the base activator fixed makes the total effect of external borax addition measurable, but does not isolate a boron-only effect.

Routine X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS) can constrain these interpretations when used together. They do not, by themselves,

identify a unique atomistic mechanism. A shifted silicate band is not specific proof of boron incorporation; an apparently denser fracture surface is not a quantitative measure of gel yield. The appropriate outcome of a first study may therefore be a supported kinetic and microstructural association, with targeted boron-sensitive measurements reserved for stronger structural claims.

4. Proposed Research Framework for External Anhydrous Borax Addition

4.1. Define the Treatment and Preserve the Comparison

The framework uses the combined mass of fly ash and GGBFS as the precursor denominator. The external dosage, expressed in percent, is defined as $DB = 100 \text{ mB}/(\text{mFA} + \text{mGGBFS})$, where mB is the mass of anhydrous borax and the other terms are the corresponding precursor masses, all in the same units. Product purity and moisture uptake should be reported; any purity correction should be identified separately from the as-weighed dosage.

Within each base concrete formulation, fly ash, GGBFS, sodium silicate, sodium hydroxide, effective mixing water, and aggregate quantities remain fixed as DB changes. Borax is an additional component, not a replacement for precursor or activator. Sodium supplied by borax is reported separately from the Na_2O equivalent supplied by the base activator. Thus, constant base-activator dosage must not be described as constant total sodium. Stoichiometrically, pure $\text{Na}_2\text{B}_4\text{O}_7$ contains approximately 0.308 mass units of Na_2O equivalent per unit mass of borax; this is chemical accounting, not a measured performance result or a reason to reduce the base activator.

The powder would first be checked against its product specification and mixed with the precursors using a common procedure. Activator temperature, preparation history, mixing sequence, aggregate moisture corrections, and curing conditions should be fixed after preliminary trials. In particular, a nominally ambient regime needs recorded temperature and sealing conditions. Absolute-volume yield should also be reported because adding solids without replacing another constituent changes the mixture mass and may slightly change the yield.

4.2. Screen Paste and Mortar Before Concrete Verification

Screening would begin with paste and representative mortar derived from the binder and activator proportions of the C40-target base formulation. C40 is a concrete design label; it does not classify the mortar. Removing coarse aggregate while preserving the relative amounts of the remaining ingredients provides a comparable sub-system for dose screening. It does not reproduce all constraints on concrete placement.

An initial external-dose grid of 0, 1, 2, 3, 4, 5, 6, and 8% follows the proposed experimental programme. These are screening levels, not recommended additions.

Paste setting tests would identify delayed or incomplete hardening, while mortar tests would follow flow at common elapsed times and strength development at 3, 7, and 28 days. The timing origin should be first contact between activator and precursor. Sealed storage and a common remixing procedure are needed for retained-flow measurements.

A candidate mortar dosage, D_m , would be selected only after applying predefined limits on placement time, initial flow, flow loss, segregation, and early strength. Among acceptable candidates, the trade-off between retained flow and later strength can be described as a set of non-dominated options; choosing the lowest satisfactory dose avoids equating the maximum tested response with a universal optimum. Failed or non-hardening high-dose groups should remain in the fresh-property record, even if they cannot provide valid hardened specimens.

Concrete verification would then compare the control, D_m , and two feasible neighboring dosages within each of five base formulations targeting C20–C60. The four levels must be distinct and non-negative; a lower neighbor that duplicates the control requires an alternative selected before verification. These labels represent target formulations until measured strengths establish their classification. A formulation-by-dosage interaction would indicate limited transferability of a common treatment, not an experimental failure.

If a representative dosage is supported across the verified formulations, it may subsequently be designated D_R . This decision follows concrete verification and is distinct from the mortar candidate D_m . If no common dosage satisfies the predefined requirements, formulation-specific ranges should be reported. Table 2 connects these decisions to the observations needed at each stage.

Table 2. Proposed decision sequence and evidence requirements. Entries describe planned work, not experimental findings.

Stage	Decision	Required evidence
Paste screening	Identify feasible dose range	Setting and hardening observations; retain records for non-hardening groups.
Representative mortar	Select candidate D_m	Time-dependent flow, stability, and age-specific strength against predefined limits.
Concrete verification	Assess transfer; define D_R if justified	Matched controls and distinct neighboring doses in each target formulation; independent batches.
Compressive response	Characterize treatment contrast	Local strain, stable post-peak curves, and independent model validation.
Mechanism testing	Discriminate interpretations	Matched-age calorimetry and structural measurements; consistent preparation and sampling.

This sequence makes the concrete comparison an independent validation step. Selecting a mortar candidate and testing only that treatment in concrete could establish its response relative to a control, but would give a weak basis for calling it the best concrete dosage.

4.3. Extend Strength Testing to Compressive Deformation

Compressive, splitting tensile, and flexural strengths would establish whether the selected treatment meets the intended hardened-property requirements. Strength retention should always use the matched zero-borax formulation at the same age as its denominator, and be accompanied by absolute strength values. Neither a favorable ratio nor a target-grade label establishes compliance on its own.

Full uniaxial compression curves would then compare the zero-borax control with the verified representative treatment. Noushini et al. [12] provide a relevant precedent for complete stress-strain characterization in low-calcium fly ash geopolymer concrete, but their model is not a calibrated law for borax-modified fly ash-slag concrete. Peak stress, peak strain, and post-peak response should therefore be measured before selecting a constitutive representation.

Stable post-peak acquisition requires a suitable loading-control system and deformation measurements on the specimen. Actuator travel should not be substituted directly for local axial strain. Curve-derived stiffness must be distinguished from a standard static elastic modulus obtained through its prescribed loading sequence. Likewise, the area under a stress-strain curve is an energy density over a stated integration interval, not automatically a geometry-independent fracture energy. Curves with different termination points require a common comparison limit.

Model calibration and validation should be separated by independent specimens or batches. Entire curves, rather than individual points from the same curve, belong in one partition. If only control and representative-dose states are measured, the resulting model describes a treatment contrast; it cannot identify a continuous borax-dose law. Validation should examine the descending branch and parameter stability as well as peak strength and overall fit.

4.4. Link Kinetics and Microstructure at Matched Ages

Mechanism-oriented measurements would concentrate on a representative base binder with zero borax, the selected treatment, and a higher dose that can harden but shows reproducible deterioration. The high-dose condition should be selected from observations, not assigned the label excessive merely because it is the largest amount tested. Early and later sampling ages would distinguish delayed reaction from persistent impairment.

Isothermal calorimetry would establish changes in heat-flow timing and cumulative heat, normalized to the stated precursor mass. XRD and FTIR would examine phase and spectral changes, while SEM-EDS would assess spatial heterogeneity across multiple fields. Mercury intrusion porosimetry would provide comparative information about accessible pore-entry sizes. These measurements should be linked to macro-scale specimens of corresponding composition, age, and curing history, rather than combined across unmatched conditions.

Preparation is part of the evidence chain. Zhang et al. [13] showed that drying procedures can alter the measured pore structure and phase characteristics of alkali-activated binders. A common stopping and drying protocol should therefore be evaluated and reported for all dose groups. Identical preparation improves comparability but does not guarantee an undisturbed microstructure. Pore-entry measurements and selected microscopy fields should be interpreted within their sampling limits.

The initial interpretation would test whether changes in setting and heat evolution accompany the observed strength and pore-structure response. A correlation between smaller pore-entry sizes and higher strength would support an association, not identify boron incorporation or prove causality. If chemical incorporation becomes a central claim, boron-sensitive structural characterization, such as appropriately designed solid-state nuclear magnetic resonance, should be considered alongside the routine measurements.

4.5. Preserve Independent Replication and Decision Rules

Independent mixing batches are the appropriate unit for assessing reproducibility of the treatment. Specimens cast from one batch, two halves of a broken mortar prism, and repeated flow readings do not constitute independent batches. Batch allocation should allow each dosage and base formulation to be represented independently, with randomized testing order where practicable and explicit blocking for day or material lot.

Analysis should report individual observations, batch-level summaries, uncertainty, and the reasons for missing or excluded results. With small sample sizes, distributional tests cannot establish that model assumptions are satisfied. A formulation-by-dosage analysis is appropriate only with sufficient independent replication and a model consistent with the allocation. Because each target strength uses a different base mixture, a formulation effect cannot be attributed to one constituent without additional control. Dosage selection should be checked for sensitivity to the chosen acceptance limits, and uncertainty should remain visible when no candidate clearly dominates.

5. Engineering Implications and Research Priorities

The literature supports investigating borate additions as reaction-control tools, while the proposed framework defines what would make such an investigation useful for concrete production. A practical treatment must provide a reproducible placement interval, acceptable stability, and adequate hardening under the intended curing regime. Its value should be expressed through these outcomes and their variation between batches, rather than through the longest achievable setting delay. Three questions remain central for anhydrous external addition. First, a dose window must be established for the actual precursor and activator combination.

Second, the persistence of that window across concrete formulations must be tested independently of mortar selection. Third, any change in compressive deformation must be connected to an adequately constrained kinetic and microstructural explanation. Long-term shrinkage, durability, and field placement lie beyond this initial verification and would be needed before broader structural or service-life recommendations.

The review is limited by its purposive selection and by incomplete access to some experimental methods. Consequently, it identifies conditions governing evidence transfer rather than a universal ranking of borax formulations. Its framework is intended to make subsequent results interpretable, including null effects, strength penalties, or the absence of a satisfactory common dosage.

6. Conclusions

Borate-containing additives have delayed setting in several alkali-activated systems, but their mechanical consequences vary with composition, activation route, and age. Anhydrous borax, hydrated borax, and combined-admixture treatments cannot be treated as chemically equivalent evidence. Published dosage recommendations therefore do not establish an optimum for externally added anhydrous borax in fly ash-slag geopolymer concrete.

A defensible evaluation begins with a precursor-based dose definition and an unchanged base formulation, while separately accounting for borax-derived sodium. Paste and mortar screening should identify candidates under predefined fresh- and hardened-property constraints, followed by independent verification in concrete. Complete compression curves and matched-age characterization can then assess the consequences of a representative treatment without assuming that delayed setting improves all aspects of performance.

The proposed framework connects practical dosage selection with limits on causal interpretation. Surface inhibition and network modification remain alternative mechanisms to be tested in the specified system. No experimentally established dosage, strength benefit, or constitutive parameter is claimed by the present review.

Conflicts of Interest

[Author to confirm any financial or non-financial competing interests before submission.]

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

OpenAI Codex was used to assist with literature discovery, evidence organization, development of the manuscript structure, drafting, language revision, and reference formatting. The author is responsible for verifying the cited sources, scientific interpretations, and final text before submission.

Data Availability

No new experimental data were generated or analyzed in this narrative review. The literature sources supporting the synthesis are identified in the reference list.

References

- [1] Nath, P. and Sarker, P.K. (2014) Effect of GGBFS on Setting, Workability and Early Strength Properties of Fly Ash Geopolymer Concrete Cured in Ambient Condition. *Construction and Building Materials*, 66, 163–171. <https://doi.org/10.1016/j.conbuildmat.2014.05.080>
- [2] Ben Haha, M., Le Saout, G., Winnefeld, F. and Lothenbach, B. (2011) Influence of Activator Type on Hydration Kinetics, Hydrate Assemblage and Microstructural Development of Alkali Activated Blast-Furnace Slags. *Cement and Concrete Research*, 41(3), 301–310. <https://doi.org/10.1016/j.cemconres.2010.11.016>
- [3] Ismail, I., Bernal, S.A., Provis, J.L., San Nicolas, R., Hamdan, S. and van Deventer, J.S.J. (2014) Modification of Phase Evolution in Alkali-Activated Blast Furnace Slag by the Incorporation of Fly Ash. *Cement and Concrete Composites*, 45, 125–135. <https://doi.org/10.1016/j.cemconcomp.2013.09.006>
- [4] Garcia-Lodeiro, I., Palomo, A., Fernández-Jiménez, A. and Macphee, D.E. (2011) Compatibility Studies between N-A-S-H and C-A-S-H Gels. Study in the Ternary Diagram $\text{Na}_2\text{O}-\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$. *Cement and Concrete Research*, 41(9), 923–931. <https://doi.org/10.1016/j.cemconres.2011.05.006>
- [5] Liu, H., Sanjayan, J.G. and Bu, Y. (2017) The Application of Sodium Hydroxide and Anhydrous Borax as Composite Activator of Class F Fly Ash for Extending Setting Time. *Fuel*, 206, 534–540. <https://doi.org/10.1016/j.fuel.2017.06.049>
- [6] Li, P., Chen, D., Jia, Z., Li, Y., Li, S. and Yu, B. (2023) Effects of Borax, Sucrose, and Citric Acid on the Setting Time and Mechanical Properties of Alkali-Activated Slag. *Materials*, 16(8), 3010. <https://doi.org/10.3390/ma16083010>
- [7] Yousefi Oderji, S., Chen, B. and Mohseni, E. (2023) The Efficiency of Borax as an Additive on Properties of One-Part Fly Ash/Slag-Based Alkali-Activated Materials. *European Journal of Environmental and Civil Engineering*, 27(14), 4237–4249. <https://doi.org/10.1080/19648189.2023.2182367>
- [8] Hanani, E., Satyarno, I. and Sulistyono, D. (2024) Mix Design of Ambient Cured Geopolymer Concrete with Fly Ash, GGBFS, and Borax. *INERSIA: Informasi dan Ekspose Hasil Riset Teknik Sipil dan Arsitektur*, 20(2), 265–276. <https://doi.org/10.21831/inersia.v20i2.74464>
- [9] Tran, M.V., Vu, T.H. and Nguyen, T.H.Y. (2023) Simplified Assessment for One-Part 3D-Printable Geopolymer Concrete Based on Slump and Slump Flow Measurements. *Case Studies in Construction Materials*, 18, e01889. <https://doi.org/10.1016/j.cscm.2023.e01889>
- [10] Yu, H., Zhou, Y., Xia, W. and Xu, T. (2025) Synergistic Mechanism and Performance Enhancement of Fly Ash-Slag-Based Geopolymer with Sodium Tetraborate and Aminopropyltriethoxysilane for Retardation. *Construction and Building Materials*, 487, 142055. <https://doi.org/10.1016/j.conbuildmat.2025.142055>
- [11] Wang, J., Han, L., Liu, Z. and Wang, D. (2020) Setting Controlling of Lithium Slag-Based Geopolymer by Activator and Sodium Tetraborate as a Retarder and Its Effects on Mortar Properties. *Cement and Concrete Composites*, 110, 103598. <https://doi.org/10.1016/j.cemconcomp.2020.103598>
- [12] Noushini, A., Aslani, F., Castel, A., Gilbert, R.I., Uy, B. and Foster, S. (2016) Compressive Stress-Strain Model for Low-Calcium Fly Ash-Based Geopolymer and Heat-Cured Portland Cement Concrete. *Cement and Concrete Composites*, 73, 136–146. <https://doi.org/10.1016/j.cemconcomp.2016.07.004>
- [13] Zhang, Z., Zhu, Y., Zhu, H., Zhang, Y., Provis, J.L. and Wang, H. (2019) Effect of Drying

Procedures on Pore Structure and Phase Evolution of Alkali-Activated Cements. *Cement and Concrete Composites*, 96, 194–203.
<https://doi.org/10.1016/j.cemconcomp.2018.12.003>