

Ferricrete-Bearing Lateritic Soils For Unfired Masonry: Mineralogical Controls On Hydro-Mechanical Performance And Durability — A Systematic Review

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Abstract: Ferricrete-bearing lateritic soils are promising geomaterials for unfired masonry because their iron-oxide-rich mineralogy can improve strength and durability while supporting low-temperature construction. This systematic review examines how ferricrete mineralogy, particularly hematite-goethite balance and textural class, influences the hydro-mechanical performance of unfired lateritic masonry through a structured synthesis of published studies on mineralogy, microstructure, stabilization, curing, and durability. The reviewed evidence shows that higher ferricrete indices are generally associated with greater compressive strength, lower water absorption, reduced sorptivity, and improved resistance to wetting-related degradation when compatible binder systems and controlled curing conditions promote gel-oxide interlocking and pore-network refinement. However, the same ferricrete-related densification may also increase brittleness if compaction, gradation, and curing are not adjusted to the source material. The findings indicate that ferricrete-bearing lateritic soils should be evaluated as performance-based geomaterials rather than as a single material class defined only by origin. Overall, their wider engineering use depends on standardized ferricrete characterization, qualification-oriented durability testing, and field validation under service-relevant environmental conditions.

Keywords: ferricrete-bearing lateritic soils; unfired masonry; hydro-mechanical performance; mineralogical controls; low-temperature stabilization.

1. Introduction

Ferricrete-bearing lateritic soils are widely distributed tropical geomaterials whose engineering behavior is governed by the interaction of iron-oxide cementation, clay mineralogy, pore structure, and moisture sensitivity [1], [2], [3]. In unfired masonry applications, these coupled features control compressive strength, stiffness, water transport, dimensional stability, and resistance to hydric degradation, making ferricrete-rich laterites both technically promising and difficult to generalize across sources [4], [5], [6]. Although unfired lateritic units are increasingly recognized as low-carbon alternatives to fired materials, their field performance still depends on how mineralogical heterogeneity is translated into measurable engineering properties under practical stabilization and curing conditions [7], [8], [9]. Understanding this mineralogy–microstructure–property relationship is therefore essential for evaluating ferricrete-bearing lateritic soils as engineerable geomaterials rather than treating them simply as locally available construction materials.

Within the lateritic soil family, ferricrete—duricrusts and cemented horizons rich in goethite and hematite—plays a pivotal role in determining engineering performance. Ferricrete phases influence particle contacts, pore-network topology, and capillary transport, thereby conditioning compressive strength and hydric durability in unfired bricks. Mechanistic interpretations and microscopy show that goethite- and hematite-bearing grains act as nucleation and anchoring sites for hydrates and aluminosilicate gels during stabilization, promoting interfacial “gel–oxide interlocking” and fabric densification [4]. Ferricrete does not act in isolation: clay assemblages (e.g., kaolinite versus smectite) co-determine plasticity, workability, water uptake, and shrinkage sensitivity, shaping the process windows available to designers [3]. These coupled mineralogical controls motivate an operational ferricrete index—combining Fe-phase proportions with textural cues—to anticipate microstructural evolution and, ultimately, macroscopic performance in unfired units. **Figure 1** synthesizes this causal pathway, linking the ferricrete index (hematite/goethite × texture) to pore-network refinement, gel–oxide interlocking, and the resulting mechanical and hydric performance [10].

From a sustainability and resource-efficiency standpoint, unfired lateritic bricks achieve large energy savings because they can be cured at ambient or moderately elevated temperatures rather than fired. Reviews and experimental programs indicate energy demands on the order of one tenth (or less) of those for conventional fired ceramics, with compatible strength development when binders and curing regimes are tuned to the host mineralogy [7]. Circular-economy routes—such as incorporating industrial or agro-residues—are increasingly documented as viable pathways to modulate density, reduce water absorption, and tailor thermal inertia, albeit with acknowledged mechanical–thermal trade-offs that must be managed through mix design [11], [12]. Despite these advantages, social acceptance and market uptake are often constrained by perceptions of durability and concerns about production consistency, underscoring the need for evidence-based guidelines and standards-aligned reporting [13].

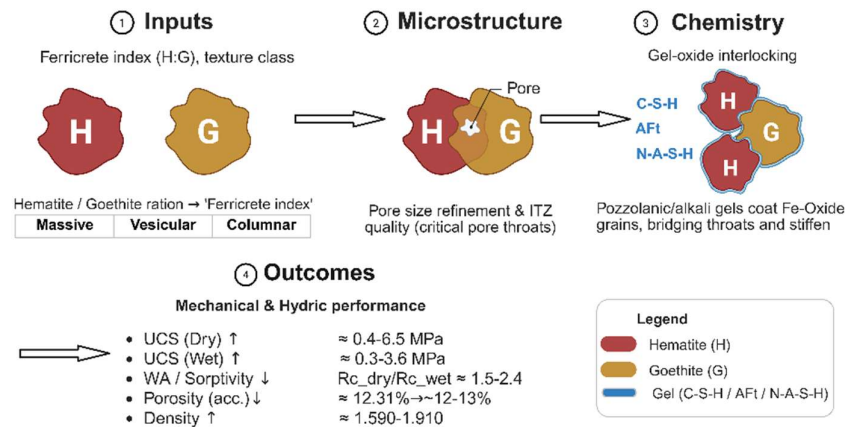


Figure 1: causal pathway, linking the ferricrete index (hematite/goethite × texture) to pore network refinement, gel–oxide interlocking

Durability is the core technical barrier for wider adoption, especially in humid tropical climates where hydric mechanisms dominate deterioration. Capillary rise, wetting–drying cycles, salt crystallization, and—at higher latitudes or altitudes—freeze–thaw action drive microcracking and strength loss when pore systems are coarse or highly connected. Damage pathways are well described in the masonry literature, which links the evolution of pore-size distributions and throat constrictions to mass transport, crystallization pressures, and cyclic stresses [14]. In ferricrete-bearing matrices, these risks are expected to depend on the hematite/goethite balance and texture class, which together govern connectivity and the quality of the interfacial transition zone when hydrates form. Consequently, stabilization strategies and curing profiles that favor pore refinement and robust gel–oxide interfaces are central to enhancing hydric resistance without resorting to firing.

Codification provides a practical frame for judging whether unfired lateritic bricks meet basic performance thresholds. Widely cited earthen-construction benchmarks require minimum unconfined compressive strength on the order of 2.9 MPa (dry) and 1.0 MPa (wet), with companion limits on water absorption to reduce moisture-induced damage [15], [16]. Aligning ferricrete-informed mix design with such criteria is critical for mainstreaming, because it translates mineralogical reasoning into testable targets that specifiers can adopt. In parallel, reporting conventions that include specimen geometry, curing temperature and relative humidity, and a standard set of hydric metrics (e.g., water absorption, softening coefficient, sorptivity, and, where relevant, freeze–thaw loss) are needed to enable meaningful cross-study comparisons and to accelerate the uptake of best practices [7], [17].

Against this background, the present study conducts a systematic literature review (SLR) of ferricrete-bearing lateritic soils for unfired brick applications. The review is scoped to peer-reviewed work published from 2016 to 2025 and focuses on compressed stabilized earth blocks (CSEB), adobe, and related unfired units cured at or below 150 °C. Stabilization pathways considered include lime and cement, ground-granulated blast-furnace slag and other industrial by-products, alkali activation systems, and selected biogenic or fibrous additives consistent with circular-economy practice [7], [12]. Fired ceramics are referenced only as performance benchmarks. The SLR is organized to (i) clarify mineralogy–microstructure–property linkages that explain how ferricrete phases modify strength and hydric behavior; (ii) operationalize an index that integrates Fe-phase proportions and texture to guide feedstock selection and mix design; (iii) evaluate stabilization and curing routes feasible at ≤ 150 °C; (iv) synthesize durability outcomes under hydric stressors and discuss the role of surface protections; and (v) position findings against standards to identify research and implementation gaps [16], [17].

In sum, lateritic unfired bricks present a compelling low-carbon alternative to conventional fired units when mineralogy is leveraged rather than treated as a constraint. Ferricrete—through its goethite/hematite balance and texture—offers designers a handle on pore-network refinement and interfacial bonding, both essential to mechanical performance and environmental durability. Building a mineralogy-based design framework that is explicitly tied to standards can, therefore, accelerate adoption and de-risk implementation. We hypothesize that a higher ferricrete index (hematite/goethite $\times$ texture) refines pore networks and strengthens gel–oxide interlocking, thereby increasing strength and hydric durability under ≤ 150 °C curing conditions [7], [8], [17].

2. Methods

2.1 Search design

This study adopts a Systematic Literature Review (SLR) to synthesize peer-reviewed evidence on ferricrete-bearing lateritic soils for unfired masonry. The SLR ensures a transparent, reproducible, and rigorous process for evidence synthesis in line with international best practice. The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) to ensure high reporting quality and transparency [18]. Scopus served as the sole bibliographic database.

2.2 Search strategy, inclusion and exclusion criteria

A structured search was conducted in Scopus using predefined keywords and Boolean operators to capture studies on lateritic soils, ferricrete-related mineralogy, unfired masonry, durability, and microstructure. The final, scoped Boolean query was: *(TITLE-ABS-KEY ((laterit* OR ferricrete OR cuirass OR "ferruginous crust" OR "bauxitic cuirass" OR brick OR masonry) AND (durabil* OR harden* OR "wet-dry" OR "wetting and drying" OR weathering) AND (mineralog* OR microstructur* OR XRD OR SEM) AND (bio* OR unfire*))*. The search results were exported to reference-management software for duplicate removal and screening. Study selection proceeded through title and abstract screening followed by full-text eligibility assessment. **Figure 2** presents the study selection workflow. The search returned 141 records, of which 53 studies were retained for qualitative synthesis after screening against the predefined eligibility criteria.

To ensure the relevance and quality of the review, studies were selected based on explicit inclusion and exclusion criteria. Studies were included if they met all of the following criteria: (i) peer-reviewed journal articles published in English

between 2016 and 2025; (ii) investigation of lateritic soils or ferricrete-bearing lateritic materials relevant to unfired bricks, compressed stabilized earth blocks, adobe; (iii) evaluation of stabilization and curing curing $\leq 150^{\circ}\text{C}$, except where fired products were used only as external benchmarks; and (iv) reporting of measurable engineering outcomes, including mechanical performance, hydric performance, mineralogical characterization, microstructural evidence, or a combination of these.

Studies were excluded if they were book chapters, conference abstracts without sufficient methodological detail, non-English publications, review papers used only for background context, studies focused exclusively on fired ceramics ($> 150^{\circ}\text{C}$), studies on non-lateritic soils without relevant Fe-oxide or mineralogical information, duplicate records lacking quantitative data or clear methodology from the database search. Table 1 summarizes these criteria.

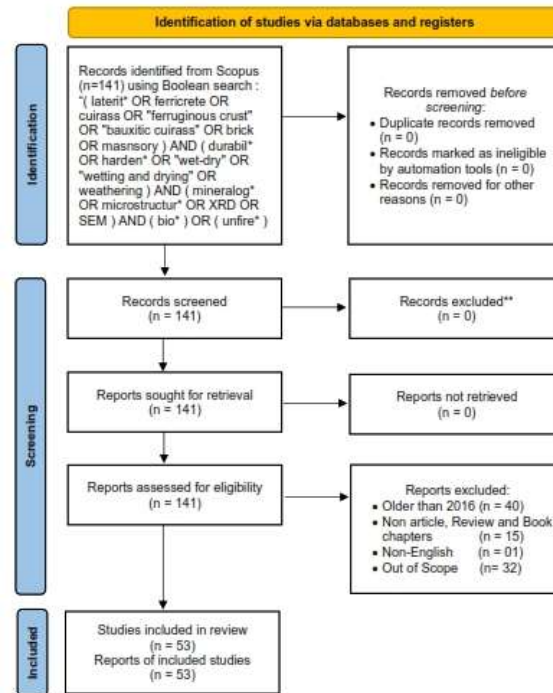


Figure 2: The PRISMA flow diagram detailing the screening and selection process of literature

Table 1: Summary of inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles, reviews published between 2016 and 2025	Book chapters, and articles published prior to 2016
Written in English	Non-English language publications
Studies providing quantified mechanical and/or hydric performance data (e.g., UCS, WA, softening coefficient)	Non-lateritic soils without Fe oxide data
Articles reporting ferricrete-related mineralogy, microstructure (SEM/XRD data), or horizon-level textural characteristics	Records lacking DOI or insufficient methodological detail
Studies investigating stabilization and curing $\leq 150^{\circ}\text{C}$	Studies focusing exclusively on fired bricks at temperatures $>150^{\circ}\text{C}$

2.3 Data extraction, thematic analysis and limitations

A standardized data-extraction form was used to collect key information from each eligible study, including provenance and a ferricrete proxy (hematite/goethite balance or horizon texture), stabilizer type and dosage, processing and curing conditions (pressing, temperature, relative humidity, time ≤ 150 °C), specimen geometry/standard, mechanical outcomes (e.g., UCS, modulus), hydric outcomes (e.g., water absorption, sorptivity, softening coefficient, freeze–thaw/salt loss), and microstructure (XRD, SEM, MIP). Thematic analysis then grouped results into (i) mineralogy–microstructure–property linkages, (ii) stabilization and ≤ 150 °C curing routes, and (iii) hydric durability and surface protections. Study quality was appraised using a brief six-item checklist (scored 0–2), and higher-quality studies were weighted more heavily in the narrative synthesis.

Despite rigorous procedures, using a single database (Scopus) may have excluded relevant studies indexed elsewhere. Short-term laboratory reporting and heterogeneity in specimen geometry, curing profiles, and durability protocols limit comparability and generalizability. Publication bias toward positive results is possible. These factors inform interpretation and motivate the research agenda presented later.

3. Theoretical Framework

3.1 Principles of ferricrete genesis, typology, and pore-network formation

Ferricrete is a pedogenic–lithogenic ironstone produced by prolonged weathering in which desilicification, fluctuating redox conditions, and lateral throughflow mobilize Fe from primary silicates and re-precipitate it as goethite and/or hematite that cement the matrix. Microbial mediation can accelerate Fe precipitation in near-surface hydrologic domains, adding amorphous precursors that mature to crystalline oxides under climatic oscillations [1], [2]. The resulting cuirasses display massive, vesicular, or pisolitic fabrics whose pore-network topology and reactive surface area are critical to unfired-brick performance [5], [19], [20].

Weathering intensity provides practical proxies for feedstock screening. Along basaltic laterite profiles, transformation from goethitic to more hematitic assemblages' tracks maturity and is captured by Fe-isotope partitioning and mineralogical markers [21], [22]. At landscape scale, multi-episode cuirass building and reworking generate textural heterogeneity that governs capillary access and blend design during processing [1], [23], [24]. Across these settings, quartz–hematitic types are typically denser with lower connected porosity than quartz–goethitic types, a difference that often aligns with lower water absorption and higher compressive stiffness at comparable compaction [5], [19]. **Fig. 3** shows these typological end-members and the indicative windows used later for interpretation; additionally, **Table 2** summarizes the genesis/typology cues and associated pore-network implications for early feedstock screening.

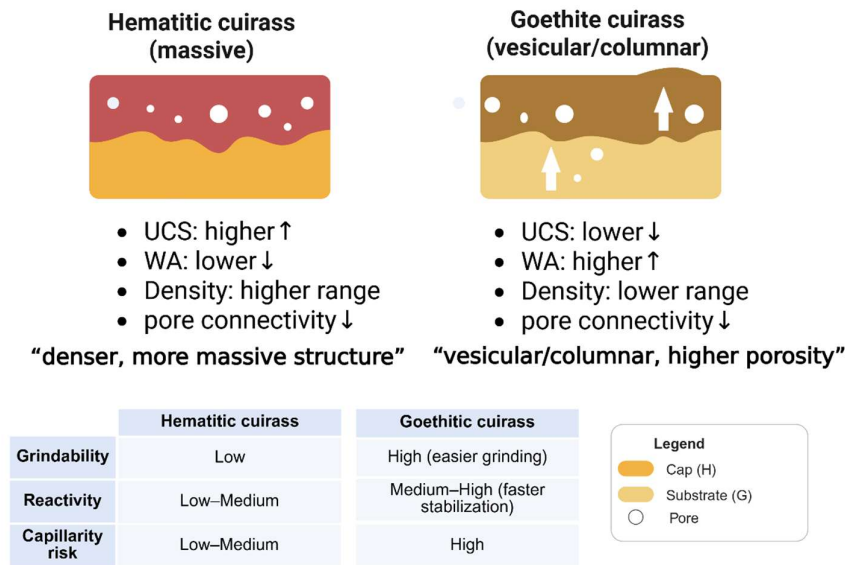


Figure 3: Ferricrete typologies (hematitic vs. goethitic cuirasses) and indicative property windows for lateritic brick feedstocks

Table 2: Ferricrete index operationalization (genesis, typology, horizon cues)

References	Regions	Horizon descriptor	Dominant Fe phases (% if given)	Clay assemblage	Texture (massive/vesicular/columnar)	Measurement method(s)	Assigned Ferricrete Index (0-1)	Notes
[23]	Burringurrah (Mount Augustus), W. Australia	Valley-bottom cuirass; high-level trail ferricrete; ferruginous conglomerate	Goethite» Hematite (qual.), Fe ₂ O ₃ total 4–36% (site dependent)	Kaolinite, muscovite, quartz; minor feldspars	Vermiform–vesicular to massive conglomeratic	Field log, thin section, XRD, geochem	0.80	Strong Fe-oxide cementation; lateral Fe transport emphasized
[21]	Hainan basalt lateritic profile	Lateritic duricrust over basalt	Goethite–hematite; Fe isotope partitioning	Kaolinite, gibbsite (local)	Massive to pisolitic	Fe isotopes, XRD	0.75	Isotopic evidence for weathering intensity
[25]	Granada (Alhambra Formation soils)	Fe-oxyhydroxide-bearing brick feed soils	Goethite/hematite evolution with firing	Illite–kaolinite + OM	Fine granular	XRD, thermal, microscopy	0.50	Shows Fe & OM control on brick texture compatibility
[24]	Iberia (lateritic remnants)	Residual cuirass (regional synthesis)	Hematite–goethite (qual.)	Kaolinite/gibbsite	Massive–pisolitic	Literature synthesis	0.65	Regional variability; guidance for sourcing
[22]	South China (laterite systems)	Laterite profile over basalts	Hematite/goethite (isotopic)	Kaolinite	Massive	Fe isotopes, XRD	0.70	Weathering intensity proxy for feedstock selection

3.2 Micromechanics of gel–oxide interlocking and ≤150 °C stabilization mechanisms

At the particle scale, unfired lateritic matrices strengthen by two interacting pathways. **Gel–oxide interlocking** denotes nucleation and growth of C–S–H/C–A–H/AfT or N(A)SH/C(N)ASH gels on Fe-oxide-coated grains, creating anchored bridges observable as bonded contacts and refined pore throats; **densification** reflects packing-driven porosity reduction with limited chemical bonding and higher susceptibility to wet-softening. SEM/XRD/MIP signatures separating these pathways are reported across lateritic systems [4], [26], [27], [28].

Low-temperature routes ($\leq 150^\circ\text{C}$) operationalize these mechanisms. Calcium-based powders promote early C–S–H/C–A–H and ettringite (AFt) that coat Fe-oxide surfaces and tighten the interparticle skeleton [29]. Hybrid cement–GGBS (ground-granulated blast-furnace slag)–lime–gypsum systems yield C–S–H + AFt for pore filling and interfacial bonding, frequently achieving code-level strengths with low water absorption (WA) [30]. Alkali activation of iron-rich laterites forms N(A)SH/C(N)ASH networks that interlock with oxide coatings and refine pore connectivity at very low curing temperatures [31]. Fiber assistance (Polypropylene or Plant fibers) further bridges flaws and modulates shrinkage; cement + fly ash + PP fiber mixes improve compressive strength and softening with acceptable freeze–thaw loss [32], [33]. Dredged-material bricks stabilized with lime/cement/fly ash satisfy brick codes under ambient curing [34]. Cement-free fly ash + thermally treated flue gas desulfurization (FGD) gypsum routes generate ettringite/AFm (aluminat–ferrite–monosulfate) and aluminosilicate gels sufficient for mid-single-digit MPa while passing wet/dry cycling [35]. Hydration studies at low temperature clarify gel windows and interfacial kinetics relevant to lateritic matrices [36], [37].

Forming pressure, green density, and specimen geometry steer the balance between strength and toughness; optimized gradation and wet grinding enhance contact and kinetics, while excessive compaction without crack-tolerant fabrics can increase brittleness [38], [39]. **Table 3** compiles the $\leq 150^\circ\text{C}$ stabilization routes—chemistry, curing conditions, expected hydrates, gel–oxide interaction, and reported strength/durability windows—used for later synthesis.

Table 3: Stabilization chemistry $\rightarrow$ microstructure $\rightarrow$ property windows ($\leq 150^\circ\text{C}$)

Reference	Stabilizer-class & chemistry	Dosage-window¶ (% binder-or- soil-mass)	Activator-/pH	Expected-gels & hydrates	Fe-oxide- interaction- (schematic)	Curing- regime- (T/RH/time)	7-/28-d- strength- window	Hydric- durability- expectation	Shrinkage-/ linear-change	Scalability-/ energy-comment
[29]	Ca-based powder (SH-85 from biomass-silica)	3–15 (opt. ≈ 9)	Alkaline Ca-bearing	C–A–H, C–S–H; ettringite	Nucleation on Fe-oxides; fabric densification	Ambient; 7–28 d	1.1 MPa at 7d ($5\times$ control); $\uparrow$ thereafter	Lower WA than control; improved cohesion	Modest; reduced with curing	Additive is low-temp. field-applicable
[30]	Cement+GGBS+quicklime+gypsum (hybrid)	Mix-optimized (NR-exact)	Alkaline; sulfate-present	C–S–H + AFt; pore-filling	C–S–H coats Fe-oxide-grains	Spray-cure; ambient	$>$ code-minima; flexural $\uparrow$	Low WA, low voids; good F–T	Low shrinkage	Uses sandy soil; industrial-by-product-synergy
[31]	Alkali activation of lateritic soil (very-low-T)	Alkali solution 10–30 wt% of solids	Na-alkali (NR-pH)	N–A–S–H; C–(N)–A–S–H	Gel-interlocking on Fe-oxide-surfaces	$\leq 150^\circ\text{C}$, up to 150 $^\circ\text{C}$	$\sigma_c \approx 13.6$ MPa (150 $^\circ\text{C}$)	WA $\approx 17\%$; softening acceptable	Slight expansion-controlled	Viable for earth-roads/blocks
[32]	Cement+fly ash+PP fiber (unfired)	Cement $\approx 9\%$; FA $\approx 2.4\%$; fiber 0.4%	Mild-alkaline	C–S–H; fiber-network	Fibers bridge Fe-coated-grains	Ambient; 14–28 d	14.5 MPa at 14d	WA 8.8%; softening 0.92; F–T loss $< 16\%$	Low shrinkage	Press-formed; scalable
[33]	Bio-fibers (P. setaceum) in adobe	0–8 wt% fiber	Neutral	Physical reinforcement; pore-templating	Fibers interact with clay–Fe matrix	Ambient	σ_c decreases with fiber; tensile split $\uparrow$	Capillary WA $\downarrow$ with more fiber	Minor; workable mixes	Thermal mass gains; bio-based
[40]	Processed lateritic FA in cement matrices	25–100% FA as sand	Cement-alkaline	C–S–H	ITZ improved with processed FA	Ambient	Mortar/conc strengths $\approx$ control	Comparable durability	NR	Substitutes river-sand
[34]	Dredged material + lime/cement/fly ash	7 mixes (NR-%)	Alkaline	C–S–H/AFt	Binds fines incl. Fe-coatings	Ambient; NM-code	Bricks meet code	Immersion pass	NR	Coastal valorization
[35]	FA + thermally-treated FGD-gypsum (cement-free)	10–50% FGDG (opt. 30%)	Alkaline (curing 60 $^\circ\text{C}$)	Ettringite/AFm; aluminosilicate-gel	NR	60 $^\circ\text{C}$ & ambient	UCS ≈ 7 –7.4 MPa	Withstood 7 wet/dry-cycles	NR	Waste-to-bricks pathway

C–S–H: calcium–silicate–hydrate;

C–A–H: calcium–aluminat–hydrate;

AFt: ettringite;

N–A–S–H: sodium-aluminosilicate hydrate;

WA: water absorption;

F–T: freeze–thaw;

NR: not reported by source.

3.3 Transport pathways, durability challenges, and design framework

Hydric transport in ferricrete-bearing matrices is governed by critical pore size, connectivity, and tortuosity. Increasing ferricrete index—via stronger Fe-oxide cementation and denser fabrics—tends to restrict capillary pathways, lowering sorptivity and moderating wet-softening at equivalent bulk porosity. However, excessive refinement without crack-tolerant fabrics can raise susceptibility to cyclic stresses. Brick studies link freeze–thaw degradation to pore-size distribution and network connectivity: refined, discontinuous networks mitigate damage compared to finer yet well-connected pores [41], [42]. These relationships motivate routine reporting of sorptivity, capillary uptake, and pore-size spectra alongside strength metrics.

Boundary conditions further condition response. Salt crystallization pressures in connected pores promote microcracking unless ingress is controlled; hydration-driven pore refinement and adequate interfacial bonding reduce this risk, while breathable surface treatments can limit liquid uptake without trapping vapor [43], [44]. For design, interpretation is aligned with common earthen-unit targets (e.g., dry UCS ≈ 2.9 MPa with application-appropriate WA limits) so that pore-network tailoring is tied to fitness-for-use.

Taken together, this framework formalizes source description via the ferricrete index (**Table 2**) and companion pore metrics, relates $\leq 150^\circ\text{C}$ stabilization windows to gel–oxide interlocking using **Table 3**, and specifies a core performance set—UCS, WA, softening coefficient, sorptivity, and freeze–thaw mass/strength loss—for consistent evaluation of unfired lateritic bricks.

4. Review of Themes

4.1 Mineralogical and textural controls on hydro-mechanical performance

4.1.1 Evidence synthesis and scope

Working within the mineralogy-microstructure-property framework established earlier, the reviewed evidence indicates that ferricrete content and texture are first-order controls on the hydro-mechanical behavior of unfired lateritic masonry units. Across compressed stabilized earth blocks (CSEB), adobe, and related low-temperature systems ($\leq 150^\circ\text{C}$), higher ferricrete indices, expressed through hematite/goethite balance and denser textural classes, are generally associated with elevating unconfined compressive strength (UCS), reduced capillary connectivity, and improved dimensional stability [2], [3], [4], [45], [46]. Representative studies show that alkali-activated lateritic systems cured at $\leq 150^\circ\text{C}$ attain UCS in the low- to mid-teen megapascal range [31], while optimized calcium-rich systems and fiber-assisted blends also produce favorable strength (≈ 14.5 MPa at 14 days) [32] and water-resistance outcomes when ferricrete-bearing matrices are adequately compacted and cured [30]. These results support the use of ferricrete descriptors as practical screening variables for anticipating pore-network refinement, interparticle bonding, and moisture-sensitive performance in unfired lateritic geomaterials.

Table 4 consolidates these ferricrete–performance linkages across representative studies—detailing materials, stabilizers, specimen geometry/pressing, curing, strength and hydric metrics, density/voids, and microscopic signatures—so that readers can see how ferricrete index and processing co-determine properties at a glance. **Table 4** also anchors subsequent microstructure-to-property discussion (**4.1.2–4.1.3**) by providing the relevant study rows for cross-reference [29], [30], [31], [32], [33], [47].

4.1.2 Mechanistic pathways: gel-oxide interlocking versus densification

Two recurrent strengthening pathways explain the performance trends observed across the retained studies. The first is **Gel–oxide interlocking** in which hydrate and aluminosilicate gels (C–S–H/C–A–H/Aft; N(A)–S–H/C(N)–A–S–H) nucleating onto Fe-oxide–coated grains to form bonded bridges and refined pore throats; The second is **densification** in which strength gains arise mainly from packing and reduced void ratio, but with less chemically anchored bonding and therefore greater sensitivity to brittle response or wet softening [4], [26], [28]. In **Table 4**, [29] and [30] exemplify interlocking via abundant C–S–H/Aft on oxide surfaces (SEM/XRD), which is consistent with lower WA and improved F–T behavior. [31] show analogous gel networks

from alkali activation at ≤ 150 °C, yielding $\sigma_c \approx 13.6$ MPa with acceptable WA. By contrast, fiber-templated adobes [33] emphasize pore architecture and crack bridging, exchanging peak UCS for ductility and reduced capillary uptake—useful for brittleness management. The composite route in [38] demonstrates hybrid behavior: gel interlocking from cementitious reactions plus micro-bridging from PP fibers, which together support softening coefficients near 0.9 and restrained F–T losses.

Complementary spectroscopic cues support the distinction: Mössbauer resolves Fe valence states consistent with polymerized gels in interlocked systems [4], while smoother contacts and limited phase development typify densified matrices [26]. Read horizontally across **Table 4**—from stabilizer class to microstructure and failure mode—and the microstructure to property linkage becomes explicit: rows with interlocking signatures align with low WA/robust softening, whereas rows dominated by densification show greater brittleness risk. This cluster logic operationalizes the earlier causal chain without further repetition.

4.1.3 Process variables, source texture, and brittleness management

The beneficial effect of ferricrete is strongly conditioned by processing. Compaction, curing profile, particle-size distribution, and source texture determine whether ferricrete-bearing matrices develop robust interfacial bonding or become overly stiff and brittle. Forming pressure, curing profile, and particle gradation modulate the same microstructural levers. Increasing compaction raises contact areas and accelerates interfacial bonding, but excessive compaction without crack-tolerant fabrics promotes brittle failure. A single benchmark retained for concision is the ≈ 14.5 MPa UCS at 14 days under ≈ 20 MPa pressing for a cement–fly ash–PP fiber system [32]. Geometry and loading rate also affect apparent strength, necessitating explicit reporting for comparability [48]. To temper brittleness while preserving the ferricrete-enabled hydric benefits, the literature converges on (i) short fibers for crack bridging, (ii) gradation optimization/wet grinding to improve packing without over-stiffening, and (iii) hybrid binders that sustain gel yield at lower shrinkage [29], [30], [32], [33]. These trends are contextualized in **Table 4** and used downstream in the stabilization and durability synthesis (Sections 4.2–4.3).

In practice, mitigation packages are most effective when tuned to source texture: vesicular feedstocks benefit from limited fiber addition plus pore-throat refiners (e.g., glass-rich or calcium-sulfate blends), while massive sources tolerate higher compaction but require attention to shrinkage. The failure-mode column in **Table 4** (brittle vs ductile vs shear/splitting) provides quick diagnostics to select the appropriate package without reiterating the framework.

4.1.4 Provenance & typology implications for mix design

Because the ferricrete index is ultimately geological, provenance and typology must inform mix design. Hematitic, massive cuirasses typically provide dense, low-connectivity fabrics favorable to strength/WA targets, while goethitic, vesicular/columnar horizons are more reactive but risk higher capillarity unless pore-throat refinement strategies are built in [2], [21], [45], [46], [49]. Fe-isotope fingerprints (e.g., $\delta^{56}\text{Fe}$) and trace-suite screens (Ni/Cr/Mn) provide practical provenance tools that correlate with color development, densification windows, and stiffness evolution in lateritic bricks [1], [50], [51].

Table 5 organizes climate–tectonic setting, profile architecture, Fe-phase prevalence, clay assemblage, impurity suites (Ni/Cr/Mn hosts), and processing implications across regions [1], [23], [50], [51], [52], [53], [54]. Designers can then select/blend sources and set grinding targets that favor gel–oxide interlocking pathways identified earlier.

Table 4: Ferricrete–performance mechanisms in unfired/lower *T* lateritic bricks

Reference	Soil/material & ferricrete descriptor	Stabilizer/ activator & dosage	Specimen geometry / forming pressure	Curing regime (T/RH/ time)	UCS / UTS / Modulus (age)	Water absorption / Sorptivity	Softening coeff. / F-T loss	Density / voids	Microstructure (XRD/SEM/MIP)	Failure mode	Notes on mix/ workability
[29]	Tropical laterite (Fe-oxide coated clays)	SH-85, 3–15% (opt. 9%)	Ø50×100 mm; statically compacted	Ambient 7–28 d	UCS 1.09 MPa on 7d (5× control)	↓WA vs control	NR	↑bulk density; ↓voids	C-A-H/C-S-H gels on grains; denser fabric	Brittle at high dosage	Optimum around 9%
[31]	Lateritic soil; ferricrete-bearing	Na-alkali 10–30% (solids)	Prismatic (NR); pressed	28°C–150 °C	σc 13.6 MPa at 150 °C; flexural 6.6 MPa	WA 17%	Softening acceptable	ρ 1.77 g/cm³; porosity 30%	XRD/FTIR confirm gels; SEM compact	Brittle – ductile transition	Low-temp strengthened laterite
[32]	Aeolian sand–loess composite (Fe-bearing fines)	Cement 9% + FA 2.4% + PP fiber 0.4%	Pressing 20 MPa	Ambient	UCS 14.5 MPa on 14d	WA 8.8%	Softening 0.92; F-T Δσ 15.9%	NR	SEM: gel bridges; fiber network	Shear - splitting	Optimal ratio reported
[30]	Sandy soil (lateritic influence possible)	Cement+GGBS+lime+gypsum (opt.)	Molded bricks	Spray-cure d; ambient	Meets code; flexural ↑	Low WA; low voids	Excellent F-T, immersion	Dense	C-S-H+AFt	Brittle	Particle gradation key
[33]	Adobe matrix with <i>P. setaceum</i> fibers	Fibers 0–8%wt (no cement)	Molds; tamped	Ambient	σc↓ with fiber; split ↑	Capillary WA ↓	NR	ρ↓ with fiber	SEM: pore templating	Ductile	
[47]	Glauconite clay mortar (Fe-rich)	Methylcellulose 0.2–0.6%	Mortar prisms	Ambient	σc ↑ up to 35%	Water resistance ↑; shrinkage ↓	NR	NR	SEM: denser matrix	NR	Relevant to binder for CSEB

Table 5: Ferricrete genesis, typology & regional/process controls

Reference	Region & climatic setting	Profile architecture / horizon thickness	Dominant Fe phases & %	Clay assemblage	Lateral derivation / biogenic mediation	Impurity metals (Ni/Cr/Mn) & hosts	Implications for raw-material selection	Processing notes
[23]	Arid–semi-arid WA; inselberg	Valley fills; high-level crust; 2–3 m conglomeratic	Goethite±hematite; Fe2O3 4–36%	Kaolinite± muscovite	Strong lateral solution transport	Low impurities	Prefer quartz-rich massive ferricrete; avoid highly vesicular	Crushing/ screening for gradation
[55]	Tropical lagoon, New Caledonia	Shore→reef gradient	Fe-oxyhydroxides minor→clays; pyrite only nearshore	Nontronite, serpentines, glauconite	Authigenic green clay formation	Ni associated with clays	Indicates variable Fe host phases in inputs	Source blending to manage Ni
[53]	SW Vietnam shelf	Crusts/nodules	Fe-oxyhydroxides with Mn	NR	Marine processes	Mn–Fe coupled phases	Marine inputs alter Fe fingerprints	NR
[54]	Temperate palaeolandscape	Paleosol ferricrusts	Hematite/goethite	Kaolinite-rich	Pedogenic	NR	Color/texture control for bricks	NR
[21]	Monsoonal tropics (Hainan)	Laterite over basalt	Goethite→hematite; isotopic fractionation	Kaolinite/ gibbsite	Vertical weathering	Trace metals bound in oxides	Higher Fe index → higher stiffness	NR

4.2 Stabilization and ≤150 °C curing effects on hydro-mechanical behavior

4.2.1 Binder classes and early-age mechanisms

Low-temperature strength development in ferricrete-bearing lateritic systems depends on how effectively the binder chemistry exploits iron-oxide surfaces as nucleation sites. The reviewed literature identifies three main stabilization families: alkali-activated systems, calcium-based systems, and hybrid routes combining both mechanisms. Alkali-activated lateritic matrices develop sodium aluminosilicate or mixed calcium-sodium aluminosilicate gels, forming N(A)–S–H/C(N)–A–S–H networks, that interlock with ferricrete-coated particles and can deliver high compressive strength $\sigma_c \approx 13.6$ MPa at ≤150 °C well below those used in fired-brick production [31]. Calcium-based systems, including cement, lime, slag, and gypsum combinations, promote calcium-silicate-hydrate, calcium-aluminate-hydrate, and ettringite formation, improving particle bonding and reducing capillary transport when sulfate balance and curing are controlled [29], [30]. Hybrid systems with limited fiber reinforcement further reduce cracking and enhance softening resistance by combining chemical bonding with micro-bridging [32], [33]. In short, the activation/hydration pathways (etching/nucleation on Fe-oxides, followed by gel growth and pore-throat refinement) are

visible across the evidence base and are summarized in **Table 6**, which provides a process–property matrix aligned to early-age mechanisms [29], [31], [32], [34], [35].

4.2.2 Dosage windows, shrinkage control, and curing sensitivity

The performance of these systems depends not only on binder class but also on dosage, humidity, temperature, and mixing quality. Across the retained studies, the best outcomes occur when gel formation is sufficient to refine pore structure and strengthen interfaces without triggering excessive shrinkage, sulfate-related instability, or brittle behavior [29], [30], [34], [35]. Elevated curing temperature can accelerate reaction kinetics, but the benefit is reduced if relative humidity is poorly controlled or if rapid drying generates microcracking. Likewise, improved particle dispersion through wet grinding or controlled shear mixing can enhance oxide-surface exposure and promote more uniform interparticle bonding. These observations indicate that stabilization should be interpreted as a coupled chemistry-processing problem rather than as a simple function of binder dosage alone.

In **Table 6**, these windows are made explicit in the dosage and curing columns, allowing readers to cross-check shrinkage notes against strength and WA outcomes for each recipe. This layout mirrors the earlier logic—prioritizing interlocking while preventing sulfate-driven damage—without restating the theory.

4.2.3 Temperature–humidity synergy

Elevated temperature accelerates hydration/activation, yet pore refinement without brittleness requires sufficient RH to avoid microcracking and pore coarsening. In practice, ambient to ~150 °C curing under controlled RH provides stable WA reduction and softening retention when reaction fronts are sustained—principles reflected across the **Table 6** curing columns [29], [30], [31], [34], [35].

Figure 4 introduces normalized process–property “radars” for the three binder families (control = 1.0), enabling at-a-glance comparison of UCS, WA (inverted), softening coefficient, F–T resistance, and shrinkage across curing regimes; this graphical summary complements **Table 6** and maintains continuity with the mechanism-led framing.

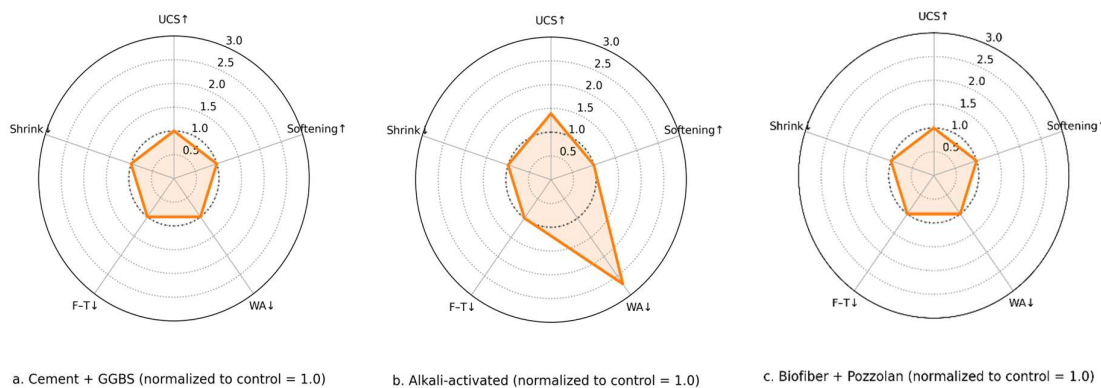


Figure 4: Normalized performance radars for stabilization classes (control = 1.0; common 0–3 scale).

4.3 Hydric durability, freeze–thaw, and pore-network connectivity

4.3.1 Metrics, mechanisms, and durability windows

Hydric durability is the decisive service-life issue for unfired ferricrete-bearing lateritic masonry, particularly in humid climates. Within the same process–transport logic, durability under hydric stress is resolved by the coupled set of WA, sorptivity, softening coefficient (wet/dry strength), and freeze–thaw (F–T) mass/strength loss, all of which are controlled by pore connectivity as modulated by ferricrete index. Across the consolidated evidence, mixes with stronger gel–oxide interlocking systematically reduce WA and preserve softening coefficients even when total porosity changes little [7], [30]. Fiber-assisted systems report softening ≈ 0.9 with moderate F–T losses when fibers restrain microcracking [32]. Heritage interface studies highlight that hydric mismatch at brick–plaster contacts can exacerbate rising damp, emphasizing the need for pore-scale compatibility [56]. In humid regimes, several studies converge on maintaining WA in the single-digit (%) range as a pragmatic target; for example, [32] the composite achieves WA $\approx 8.8\%$ while retaining softening 0.92, and low-void Ca–S–H systems in [30] meet code with low sorptivity. **Table 7** summarizes these outcomes by test type/standard, Fe-index context, and microdamage indicators, and notes that “NR” entries reflect source reporting rather than omissions by the present authors. The entries explicitly cited in the narrative span [30], [32], [33], [56], and [57], ensuring direct linkage between the table and the text. These trends confirm that durability depends more on pore connectivity and interfacial stability than on bulk porosity alone.

Table 6: Stabilization and low temperature curing strategies (process–property matrix)

Reference	Stabilizer class & chemistry	Dosage (%)	Curing T/RH/time	pH / ionic strength	Strength gain VS control (7/28 days)	Water/ chemical durability metrics	Shrinkage / linear change	Energy / embodied-carbon note	Microstructural phases	Scalability remarks
[29]	Ca-based powder (SH-85)	3–15 (opt. 9)	Ambient; 7–28 d	Alkaline	5× at 7 d	Lower WA	↓	Low-T additive	C-A-H/C-S-H	Field-deployable
[31]	Alkali activation	10–30	28–150 °C	High pH	Large ↑ (to 13.6 MPa)	WA 17%; passes code	NR	Very low firing energy	N-A-S-H	Suited to laterites
[38]	Cement+Flys ash + fiber	~12	Ambient; 14–28 d	Mild alkaline	High (14.5 MPa at 14 d)	Softening 0.92; F-T OK	Low	Press-form; no firing	C-S-H	Industrially scalable
[34]	Lime/cement/fly ash on dredged material	Mix-set	Ambient	Alkaline	Meets brick code	Immersion pass	NR	Valorizes waste	C-S-H/AFt	Coastal works
[35]	FA + FGD gypsum (cement-free)	10–50 (opt. 30)	60 °C or ambient	Alkaline	~7 MPa	Withstood 7 wet–dry	NR	Low-temp cure	Ettringite/AFm	Waste utilization

Table 7: Hydric durability, freeze–thaw & pore network

Reference	Test type / standard	Ferricrete / Fe-oxide index	Coating / treatment	Initial absorption / Sorptivity	WA% vs time	Strength loss / Softening coeff.	Mass loss / Spalling	Micro-damage indicators	Notes on comparability
[30]	WA; F-T; Immersion	NR	None	Low sorptivity	Low WA; stable	Strength retained	Minimal	SEM: dense gel	Spray-cure influences
[33]	Capillary absorption	Low–moderate Fe soils	Fiber (0–8%)	↓ with ↑fiber	WA curve lowered	σ _c ↓ with fiber	NR	SEM pores increase	Thermal benefits trade-off
[44]	WA; Softening; F-T cycles	Moderate	PP fiber 0.4%	NR	8.8%	Softening 0.92	F-T σ loss 15.9%; mass loss 1.1%	SEM microcracks restrained	Env. class MU10–15
[56]	Rising damp; hydric	NR	Lime plaster interface	High micro-porosity bricks	High WA in floor brick	NR	Gypsum weathering	Pore <2 μm prevalent	Heritage context
[57]	Salt crystallization	NR	None	NR	NR	Residual strength ↓ with more tea waste	NR	MIP: pore fa Crespo mily shift	Lightweight thermal focus
[57]	Salt crystallization	NR	None	NR	NR	Durability ↑ with recycled carbon fiber	NR	SEM fiber distribution	Salt durability emphasis

4.3.1 Textural controls

Texture sets the baseline transport regime onto which stabilization acts. Massive ferricretes generally exhibit smaller critical pore diameters and lower hydraulic connectivity, slowing ingress and decreasing sorptivity; vesicular fabrics accelerate percolation via larger, better-connected pores, with columnar variants intermediate [58], [59], [60]. These textural differences explain the spread of WA/sorptivity values recorded across **Table 7** and are consistent with the typology logic in **Table 5** [21], [23], [54]. The practical implication is that mix design and curing should aim to refine pore throats (interlocking) rather than solely reduce total porosity (densification), particularly for vesicular sources.

A direct corollary is that texture-aware benchmarks are more informative than single WA limits. When the starting fabric is vesicular, acceptable WA may need to be coupled to demonstrably low sorptivity and a softening coefficient close to unity; for massive sources, stricter WA can be met alongside higher stiffness. Table 6 marks these nuance points through the notes on comparability and microdamage indicators, enabling code-aligned but fabric-specific targets.

4.3.2 Boundary conditions: coatings and salinity-driven risks

Boundary controls can bolster durability if they remain compatible with vapor transport. Fluorinated B-72 hybrids with Ag-doped TiO₂ deliver high contact angles (≈149°) with minimal color shift and maintained vapor exchange on porous bricks [61]. Plasma-sprayed ceramic approaches offer robust hydrophobicity and UV/thermal resilience [62], [63]. However, where salts are present, ionic strength and trace-metal hosting in Fe-oxides matter: Ni/Cr/Mn partitioning and chloride-rich regimes can elevate leaching risks or modify oxide frameworks [64], [65], [66], [67]. Hence, hydric tests should be paired with salt cycling and leachate assays, as emphasized in Table 6 entries that target salt crystallization [57].

In applications where coatings are necessary, the selection logic follows two steps: (i) confirm that contact-angle gains do not excessively suppress vapor permeability; and (ii) screen for leachable impurities under saline exposure. The compatibility and “notes on comparability” fields in **Table 5** support this two-step check, keeping protection measures consistent with the transport pathways identified earlier.

4.3.3 Surface protection and compatibility in assemblies

For assemblies, vapor-permeable hydrophobes and lime–pozzolan plasters with crushed brick provide protection while respecting pore-scale compatibility. Case studies on historic substrates underline the need to match porosity and microtexture across interfaces to avoid rising-damp amplification [56]. Experimental plasters show improved moisture buffering and long-term functional stability when superabsorbent polymers or cellulose fibers are judiciously incorporated [68], [69], [70].

Table 8 collates application/retention/ ΔE and compatibility notes—including adhesion and vapor-permeability envelopes—to guide selection and field deployment [56], [61], [62], [63], [71], [72], [73]. The table sits here by design so readers can cross-walk product type, application method, and retention with the interface risks discussed above.

Table 8: Surface protection & compatibility for earthen/fired ceramics

Reference	Substrate	Coating / binder chemistry	Application & thickness	Contact angle / ΔE^*	Weathering retention (UV/acid/salt)	Antimicrobial outcomes	Effects on WA / Sorptivity / Strength	Compatibility notes (vapor perm., reversibility)
[61]	Ancient bricks	Fluorinated Paraloid B-72 + methyl-modified silica + Ag-doped TiO_2	Brush/spray; thin film	CA up to $\approx 149^\circ$; $\Delta E^* < 5$	Hydrophobicity $> 120^\circ$ after acid/alkali / salt / UV	Inhibits <i>S. aureus</i> , <i>E. coli</i> ; anti- <u>algae</u>	$\downarrow$ WA; maintained vapor exchange (ΔMp noted)	Transparent; minimal color shift
[73]	Fired bricks (interior plasters)	Lime–pozzolan plasters with crushed brick	Trowel; multi-layer	NR	NR	NR	Improved moisture buffering	Heritage-compatible
[56]	19th-c. fired bricks + lime plaster	Lime plaster (marmorino finish)	Multi-layer	NR	NR	NR	Hydric mismatch drives rising damp	Match porosity/pore size
[57]	Fired bricks	None (material modification with carbon fiber)	—	—	Salt durability $\uparrow$	—	WA/strength trade-offs	Material-level alternative to coatings

4.4 Additives & circular by-products—mechanical–thermal trade-offs

Consistent with the mechanism-to-transport cascade, the core message is a three-way trade-off among thermal inertia/insulation, strength, and permeability, moderated by ITZ quality. Bio-fibers (e.g., sisal/coir/bamboo proxies) enhance crack bridging and post-peak toughness but can depress σ_c at higher volume fractions; adobes with *P. setaceum* fibers show reduced capillary WA alongside tensile gains [33]. Biomass/fly-ash routes densify ITZs and can simultaneously lower density and WA while moderating heat flow [35], [74], [75]. Recycled glass fines contribute secondary hydrates and pore-throat refinement; recycled carbon fibers can improve salt durability while requiring careful dispersion [57], [76]. Industrial residues (e.g., iron-ore by-products; dredged fines) supply reactive silicates and fillers that stabilize ITZ chemistry and reduce WA, with ambient-cured bricks meeting code [34], [77].

Table 9 presents these four levers in a compact, comparative format—additive type and fraction, strength/thermal/hydric outcomes, and microstructural signatures—so that one can select combinations (e.g., limited fiber + glass fines) that retain low WA and acceptable softening. The table remains unchanged to preserve traceability to the source studies and the balance of benefits/risks captured there.

Table 9: Additives & circular by products (mechanical–thermal trade-offs)

Reference	Additive type & source	Fraction (%)	Particle size / fiber length	Matrix type & ferricrete note	Strength metrics	Thermal metrics (k, Cp, time-lag)	Hydric metrics (WA / capillary)	Microstructure (bonding/ITZ/pores)	Durability / leaching notes	Environmental note
[74]	Biomass (pomace) in fired bricks	0–? (NR)	NR	Fired ceramic matrix	σ _c ↓ with ↑biomass	k↓; lighter bricks	WA↑	SEM: pore templating	NR	CO ₂ ↓ via waste valorization
[33]	PS bio-fibers	0–8	Short fibers	Adobe matrix (Fe-bearing clay)	σ _c ↓; split ↑	Time-lag ↑ (≈10 h on 9 cm)	Capillary ↓	Pore templating observed	NR	Bio-based insulation
[76]	Pond ash + recycled glass sand	15% PA + 20% RGS	Sands	Concrete brick (benchmark)	σ _c 29.6 MPa	Thermal insulation ↑	NR	Microstructure less reactive	Fire resistance passes	Circular aggregates
[57]	Tea waste (TW)	0–10	Fine organics	Fired brick	σ _c ↓ with TW	k↓; diffusion↓	WA↑; porosity↑	New pore family at 1100 °C	Salt durability ↓	Lightweight thermal bricks
[57]	Recycled carbon fiber	0–10	Short fibers	Fired brick	σ _c ↓ at 10%	NR	NR	Porosity↑ with T; fiber heterogeneity	Salt durability ↑	Wind-blade waste reuse
[35]	FGD gypsum (treated) in FA bricks	10–50	Powder	Cement-free FA brick	UCS ~7 MPa	NR	Withstood 7 wet/dry	Densification	TCLP safe	Landfill diversion

5. Conclusion

This systematic review shows that ferricrete-bearing lateritic soils should be treated as hydro-mechanically responsive geomaterials whose mineralogical and textural characteristics govern the strength, moisture transport, and durability of unfired masonry units. Across the reviewed evidence, ferricrete influences engineering performance primarily through its effects on pore-network refinement, interparticle bonding, and moisture-sensitive transport, with higher ferricrete indices generally associated with increased compressive strength (UCS), lower water absorption (WA), and improved freeze-thaw (F-T) resistance to hydric degradation when curing and binder chemistry are appropriately controlled.

The synthesis further indicates that successful stabilization at temperatures ≤150°C depends on promoting durable gel-oxide interlocking while limiting shrinkage, brittle response, and transport pathways that accelerate service-life deterioration. Alkali-activated systems, calcium-based binders, and hybrid formulations can all be effective, but their performance remains strongly source-dependent and must be interpreted together with texture, clay assemblage, and curing history. For this reason, ferricrete-bearing lateritic soils should not be qualified through composition alone; they require integrated evaluation using mineralogical descriptors, microstructural evidence, and hydro-mechanical performance metrics.

The main contribution of this review is to position the ferricrete index as a practical framework for connecting source characteristics to engineering behavior and for guiding feedstock selection, mix design, and durability assessment in unfired lateritic masonry. At the same time, the review shows that progress toward broader implementation is still constrained by inconsistent ferricrete quantification, incomplete reporting of curing and testing conditions, and limited use of cyclic durability protocols across studies.

Future research should therefore prioritize standardized mineralogical screening, harmonized reporting of specimen preparation and curing conditions, and qualification-oriented durability testing that includes sorptivity, softening behavior, and cyclic environmental exposure. Field-scale validation is also needed to confirm whether laboratory gains in strength and moisture resistance remain stable under service conditions. In engineering terms, the path forward is clear: ferricrete-bearing lateritic soils can support robust unfired masonry systems, but only when they are selected, stabilized, and qualified through performance-based procedures rather than treated as interchangeable earthen materials.

6. CRediT authorship contribution statement

Solofo Roger Rakotoarisoa: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Herry Purnama, Antoine Rasoloniaina Koera:** Writing – review & editing, Supervision, Validation. **Rijalalaina Rakotosaona, Ahmad M Fuadi:** Supervision, Validation.

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No potential conflict of interest was reported by the authors.

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