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Ancient Chinese City Wall Bricks: An Integrative Review of Materials, Provenance, and Conservation

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ABSTRACT Ancient Chinese city wall bricks are engineering units, archaeological artefacts, and epigraphic records, yet the evidence is dispersed across architectural history, archaeology, materials science, building physics, and conservation engineering. This integrative critical review organizes 93 retained sources by evidential role: 40 direct studies of Chinese city walls or Great Wall materials (E1), 11 contextual studies of related Chinese heritage materials (E2), and 42 transferable mechanistic or normative sources (E3). Synthesis-generated propositions are explicitly labelled as hypotheses (E4). The evidence is arranged along a whole-life sequence from raw material and firing to circulation, masonry, weathering, diagnosis, and repair. Three conclusions emerge. First, pore-network and transport characteristics mediate moisture-, salt-, and frost-related durability, but must be evaluated with strength, soluble salts, drying behaviour, and interface compatibility. Second, published property values are only partly commensurable because studies mix specimen roles, porosity definitions, geometries, moisture states, and direct and indirect tests; the corpus supports a comparability audit, not pooled material constants. Third, the record is historically selective: 19 of 25 direct analytical or diagnostic studies are primarily concentrated on Nanjing, Xi'an, Beijing/Linqing, or major Great Wall sectors, while only 56 of 319 seats (17.6%) in the three Nanjing brick-levy provinces had brick cladding by the early Ming. Reuse can further separate present find-spot from production and exposure history. System-level evidence remains sparse; one Ming Great Wall study reports a 100–200 μm brick–mortar transition zone. The review proposes an evidence-calibrated provenance framework, distinguishes established mechanisms from testable hypotheses such as atmospheric sulfation, and defines six priorities for comparable data, source-clay and refiring references, interface and repaired-assembly testing, long-term monitoring, provenance analysis that treats reuse explicitly, and information continuity across conservation cycles.

INDEX TERMS city wall brick, qingzhuan, pore network, provenance, salt crystallization, conservation

I. INTRODUCTION

Ancient city walls are among the largest and most materially heterogeneous categories of built heritage. Several Chinese cities retain extensive Ming–Qing wall circuits, and the Ming Great Wall crosses sharply different climatic zones. The Nanjing Ming City Wall has a surviving length of approximately 25.1 km and contains on the order of 350 million bricks, many bearing moulded or stamped inscriptions [1,2]. Across and within these monuments, however, bricks differ in raw material, firing regime, administrative grade, repair history, wall position, and exposure conditions.

The same brick is an engineering material, an archaeological artefact, and an administrative record. Its pore network and mechanical properties govern wall durability; its chemistry and mineralogy encode raw-material provenance and firing history; and its inscription may identify a producer, jurisdiction, or date. These attributes have been investigated in largely separate traditions. Historical and epigraphic work reconstructs institutions and supply [3–5]. Materials studies characterize composition and properties [6–9]. Deterioration studies examine water, salts, frost, and pollution [10–12]. Conservation studies assess treatments and repair materials [13,14]. International brick science offers transferable frameworks for firing, porosity, crystallization pressure, and compatible repair, but their applicability must be verified against Chinese materials and wall configurations [15–18].

This review asks how raw materials, firing technology, provenance, and masonry construction jointly determine the service performance, deterioration, and conservation requirements of ancient Chinese city wall bricks. Three propositions guide the analysis. P1 states that pore-network characteristics mediate water-, salt-, and frost-related durability and must be evaluated alongside mechanical and transport properties. P2 states that cross-study generalization is limited by inconsistent definitions, specimen histories, and protocols. P3 states that high-status and strategically important walls dominate the analytical corpus, while reuse and repair can decouple find-spot, production, construction date, and exposure history. These propositions organize the synthesis and are evaluated against evidence rather than treated as hypotheses statistically tested by the review.

The scope is fired clay brick used in city walls and the Great Wall, especially Ming–Qing blue, white, and inscribed bricks. Floor bricks, tomb bricks, rammed earth, timber reinforcement, and decorative brick are included only where they clarify methods, source relationships, or boundary conditions. Fig. 1 provides the organizing framework: production determines an initial material state, but reuse, weathering, and repair create feedbacks that prevent a purely linear interpretation.

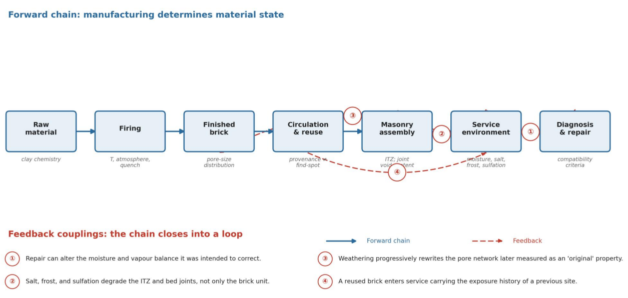

FIGURE 1. Whole-life framework. The forward chain links raw material, firing, the finished brick, circulation, masonry, service, and repair; feedbacks show how weathering, reuse, and intervention modify the state later measured as a material property.

II. REVIEW APPROACH

This article is an integrative critical review, not a protocol-registered systematic review. Searches were updated through 12 July 2026. Chinese databases comprised CNKI, Wanfang, and VIP. English-language and multidisciplinary sources comprised Web of Science, Scopus, ScienceDirect, SpringerLink, Taylor & Francis, Google Scholar, and publisher websites. English and Chinese query blocks combined heritage identifiers, brick terms, and methods or mechanisms. Backward and forward citation tracking expanded the corpus. Database-specific search strings, search dates, and final source-role counts are reported in Supplementary Table S1. Because the search evolved iteratively across disciplines, raw hit and exclusion counts were not consistently preserved and are not reconstructed retrospectively. The review is transparent about its final corpus and coverage rationale but does not meet the exhaustiveness criterion of a protocol-registered systematic review (e.g., PRISMA [19]).

Sources were coded by relevance and transferability. E1 denotes direct evidence from Chinese city walls, Great Wall sectors, or their documented brick and mortar supply systems. E2 denotes contextual evidence from other Chinese historical bricks, kilns, masonry, or earthen heritage. E3 denotes transferable mechanisms, methods, and normative frameworks that are not tied to a single city-wall material population. E4 denotes hypotheses or predictions generated by this synthesis. The retained corpus contains 93 sources: 25 Chinese-language and 68 English-language publications; by evidence role, 40 are E1, 11 E2, and 42 E3. E4 propositions are not counted as source records. The coding rubric and examples are provided in Supplementary Table S2.

Inclusion required primary data, a directly relevant historical or archaeological dataset, a mechanistic model, or a normative framework bearing on at least one link of the life-cycle chain. Purely promotional material, duplicate reports, modern brick studies without a heritage comparator, and descriptive site accounts lacking material, institutional, or diagnostic information were excluded. Extracted fields included site and period, source type, sample origin and condition, analytical method, property definition, geometry and moisture state, interpretation, uncertainty, and stated limitations. Direct analytical and diagnostic studies were separately coded by site status and research function to test P3; the 25-study audit and its coding criteria are reported in Supplementary Table S3.

Many primary studies omit specimen-level values, sample counts, uncertainty, sampling depth, and repair history. Formal meta-analysis was therefore not attempted. Numerical ranges are reported descriptively and are not pooled constants. Absolute statements such as "only study" or "no evidence" are restricted to the retained corpus and are phrased accordingly.

Because raw database hit and exclusion counts were not preserved, a PRISMA-style screening alluvial cannot be reconstructed without introducing unsupported numbers. Fig. 2 therefore visualizes the audited composition of the final 93-source corpus. Each retained source was assigned one publication-language category, one evidence role, and one primary research theme for visualization; the underlying cross-tabulations are reported in Supplementary Tables S10a and S10b.

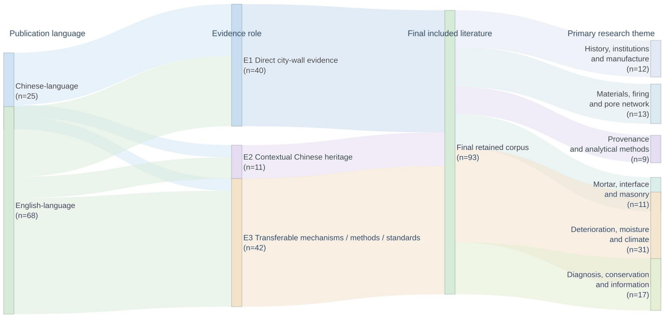

FIGURE 2. Alluvial diagram of the retained literature corpus. The 93 retained sources comprise 25 Chinese-language and 68 English-language publications. Evidence roles are E1, direct city-wall evidence (n=40); E2, contextual Chinese heritage evidence (n=11); and E3, transferable mechanisms, methods, and normative frameworks (n=42). Each source was assigned one primary theme for visualization. Raw database hit and exclusion counts were not preserved and are not retrospectively reconstructed.

III. HISTORICAL AND PRODUCTION CONTEXT

A. SELECTIVE CLADDING, SUPPLY, AND REUSE

Excavated material provides E1 evidence for brick-clad rammed-earth walls by the Eastern Han, while the earliest documentary example located in the retained corpus is the Eastern Wu inner city of Zhenjiang in 208 CE [4,20]. Brick cladding remained exceptional for centuries. Later historical interpretation associates its regional adoption with friable soils and rainfall, recurring maintenance costs, and military exigency; Song texts and excavated Chengdu bricks directly document organized county quotas and named producers under emergency construction [4,21,22]. These source types are complementary but not interchangeable: excavation establishes physical fabric, transmitted texts describe intended practice, and later scholarship supplies interpretation.

Ming-era wall construction was extensive but far from universal. In Southern Zhili, Huguang, and Jiangxi—the three provinces studied by [5] because they supplied the Nanjing levy—56 of 319 recorded prefectural, departmental, and county seats (17.6%) had brick cladding by the early Ming; among county seats the share was 5.9%. This is a regional stock figure that includes walls inherited from earlier periods and should not be generalized to China as a whole. It nevertheless shows that cladding was rationed according to administrative rank, strategic importance, and cost. The resulting research bias is measurable: 19 of the 25 direct analytical or diagnostic studies coded in Supplementary Table S3 are primarily concentrated on Nanjing, Xi'an, Beijing/Linqing, or major Great Wall sectors. Those monuments do not represent the full population of historical urban brick.

Production and consumption were also geographically separated. Kilns in Jiangxi supplied Nanjing even where the producing county lacked a brick wall, and low-priority walls were dismantled to supply guard cities and strategic centres [5,23]. A brick may consequently predate the wall in which it now stands, originate in a different jurisdiction, and carry more than one exposure history. Reuse therefore confounds provenance attribution, dimensional dating, and deterioration modelling; chemical analysis alone cannot identify reuse unless the source composition is independently known.

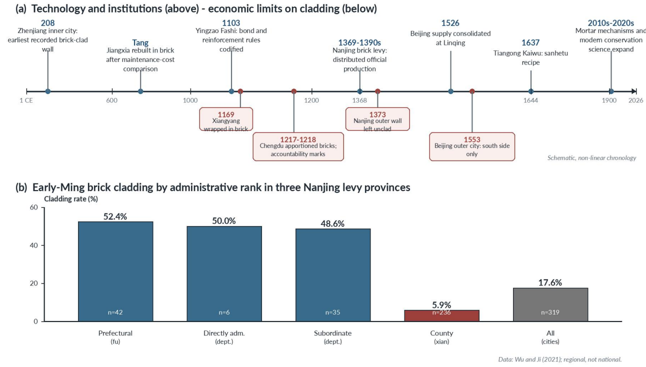

FIGURE 3. Historical development and the economic selectivity of cladding. Panel (b) reports the regional dataset of [5], not a national rate.

B. INSTITUTIONS, KILNS, AND MANUFACTURE

Ming inscriptions operationalized wu le gong ming—the artefact bears the maker's name—as a traceability system linking officials, kiln households, foremen, and craftsmen. The level of inscriptional detail varied over time, especially after supply for Beijing consolidated at Linqing, but the system connected production responsibility with acceptance and payment [3,9]. Acoustic inspection—a sound brick rang when struck and revealed no gross voids when fractured—screened for firing completeness, stiffness, cracks, and macro-defects. It could not assess fine pore-size distribution, but it operated within a broader quality-control system that included reference specimens and price differentials.

Kiln archaeology adds the production context inscriptions cannot. The Cayazi Great Wall kilns in Hebei were semi-subterranean loess structures with integrated flues, while the Lichuan complex in Jiangxi yielded marked blanks in direct association with kiln remains [23,24]. Together with documentary and compositional evidence, these finds reveal a geographically distributed industry organized around clay, water, fuel, transport routes, and the construction site.

Historical and surviving craft accounts describe clay selection, soaking, treading, levigation, aging, moulding, controlled drying, loading, firing, a terminal oxygen-poor stage, water-assisted cooling (yinshui), inspection, and transport [3,25,26]. Reduction accounts for the characteristic blue-grey colour and can lower the effective liquidus through ferrous-iron fluxing, although the magnitude of this effect depends on clay chemistry. Water-assisted cooling (yinshui) plausibly helped maintain reducing conditions during the cooling stage; claims of whole-body rapid quenching, enhanced glass retention, or surface densification require verification through instrumented kiln replication. Brick dimensions are likewise process- and project-dependent: mould standards, 5–8% firing shrinkage, inspection tolerance, cutting, and reuse render size an unreliable stand-alone dating or provenance indicator [9].

TABLE I. Production and Construction Variables, With Evidence Status, That Control Later Interpretation

Stage	Primary material or evidential consequence	Representative evidence / limitation
Clay selection, levigation, aging	Bulk chemistry, particle-size distribution, plasticity, defect population	E1/E3: [3,25]. Official practice may not represent local kilns.
Peak firing and atmosphere	Phase assemblage, vitrification, pore network, colour, shrinkage	E1/E3: [7,16,28]. Temperature inferred from phases needs refiring controls.
Water-assisted cooling	Maintenance of reducing conditions; modified cooling path	E1/E4: Historical evidence is strong; whole-body quenching and glass retention remain unverified.
Inscription and inspection	Administrative provenance, traceability, screening of gross defects	E1: [3,4]. An inscription may name a jurisdiction rather than a clay source.
Bond, mortar, and cladding geometry	Interfacial contact, moisture path, assembly stiffness	E1/E4: [22,27]. Functional interpretations require section-scale testing.
Reuse and repair	Find-spot, age, provenance, and exposure history become non-equivalent	E1: [5]. Reuse generally requires stratigraphic or documentary evidence.

IV. MATERIAL PROPERTIES, FIRING, AND PROVENANCE

A. WHAT CAN—AND CANNOT—BE COMPARED

One of the most methodologically informative cross-regional studies is Shi et al. [7], who tested twenty bricks from Nanjing, Xi'an, Linqing, and the Beijing Great Wall under one protocol. Most remaining studies are site-specific. Xi'an bricks have reported bulk densities around 1.8–2.0 g cm^{-3}, water absorption around 13–18%, open porosity around 19–22%, and compressive strength around 10–12 MPa [6,29]. Beijing specimens reported by Dong et al. [9] averaged approximately 1.62 g cm^{-3} and 15.9 MPa, although individual values ranged widely. A newer E1 study characterized 21 bricks from four Beijing-area sites by WD-XRF, XRD, SEM, thermal expansion, and physical tests, and showed that sulfate and chloride weathering can obscure original compositional groupings [30]. These values orient comparison but are not pooled material constants.

The literature intermingles direct city-wall specimens with contextual historical bricks and modern references; open, total, and mercury-accessible porosity values are sometimes reported in the same column; and strengths are obtained from different specimen shapes, moisture conditions, loading protocols, or rebound-derived correlations. Sampling adds further bias: intact material is preferentially recovered, exposed surfaces may contain secondary calcite or deposited salts, and every archaeological specimen has undergone weathering. The present data therefore support an evidence map and reporting audit, not correlation analysis or formal meta-analysis. Future studies should report specimen identity and position, sample count and raw values, geometry and orientation, moisture state, loading rate, porosity definition and method, sampling depth, repair history, and uncertainty. The complete quantitative property map is provided in Supplementary Table S4, and the minimum reporting standard in Supplementary Table S5.

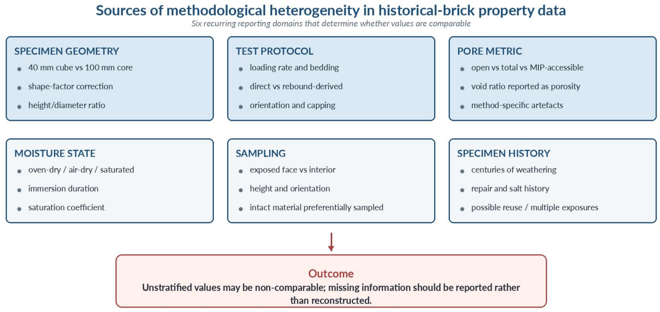

FIGURE 4. Six recurring sources of non-comparability in reported historical-brick properties. Missing information should be reported as unknown rather than reconstructed from assumptions.

TABLE II. Selected Direct Studies That Provide Harmonized Multi-Site Data, Linked Material–Mechanism Evidence, or System-Level Interface Information

Study / site	Methods and scale	Main contribution	Principal comparability limit
E1 | Shi et al. [7], four regions	Harmonized physical, mechanical, XRF/XRD, microscopy, pore analysis; n=20 bricks	Best direct cross-regional comparison; distinguishes Nanjing white and blue technologies	Small and high-status sample; weathered material only
E1 | Li C. et al. [6], Xi'an wall	XRF, XRD, optical microscopy, automated mineralogy, MIP	Dynastic differences; mineral and pore interpretation; secondary Ca recognized	Aggregated groups and uncertain exposure history
E1 | Dong et al. [9], Beijing wall	Dimensions, rebound/strength, XRF/XRD, SEM	Links inscriptions, Linqing references, chemistry, and performance	Methods and specimen preparation are not fully commensurable with other studies
E1 | Han et al. [11], Pianguan wall	Petrography, SEM, XRD/XRF, thermal and salt analyses	Links basal sulfate enrichment with cracking and surface loss	Single wall and limited environmental time series
E1 | Liu and Zhang [10], Pingyao wall	Physical properties, firing inference, salt and freeze–thaw tests	Relates pore structure, moisture, salts, frost, and conservation	Accelerated cycles do not reproduce full field exposure
E1 | Qi et al. [27], Ming Great Wall	XRF/XRD, thermal analysis, SEM, AFM, nanoindentation	Reports 100–200 μm brick–mortar transition zone and bond mechanisms	One material pair; interface variability remains unknown

B. MINERALOGY, FIRING, AND THE PORE NETWORK

Ceramic petrology provides the principal interpretive framework. Calcareous and non-calcareous clays follow different firing trajectories: decomposition of calcite and formation of Ca-rich silicates can create a coarser and more open pore system, while progressive vitrification of non-calcareous clay tends to close fine pores [15,16,31]. Strength and salt or frost resistance may therefore diverge. A calcareous brick can be mechanically strong yet vulnerable to salt or frost because the size and connectivity of its pores are unfavourable.

The Chinese evidence is consistent with more than one ceramic technology. Xi'an and Beijing blue-brick phase assemblages have been interpreted as compatible with peak firing within approximately 800–1100 °C, although the inference depends on raw material, hold time, atmosphere, and secondary carbonate formation [6,9,29]. Nanjing white bricks contain Mg-rich phases and were experimentally matched by refiring source clay above approximately 1200 °C, a substantially different trajectory from conventional blue brick [28,32]. "Ming city wall brick" therefore encompasses distinct raw-material and firing systems.

Pore-network characteristics link manufacture to service performance. MIP, nitrogen adsorption, and low-field NMR show that firing modifies the proportion, accessibility, and connectivity of fine and larger pores [8]. No single method measures the complete network. MIP primarily probes accessible pore throats and is affected by ink-bottle geometry and intrusion pressure. NMR and gas adsorption cover different size domains and require method-specific calibration. Conservation assessment should therefore use clearly defined pore-network descriptors. These descriptors should be evaluated alongside capillary uptake, drying, vapour transport, tensile capacity, soluble salts, and brick–mortar interface behaviour. Compressive strength remains essential for safety, but it is not a sufficient proxy for transport-controlled salt and frost damage. Future revision of replacement-brick standards should investigate operational pore-network and drying-compatibility criteria through interlaboratory testing while retaining mechanical requirements [18,33].

International comparison supports qualitative interpretation rather than direct performance ranking. Chinese blue brick overlaps Roman, Byzantine, and Iberian handmade brick in broad density, absorption, and strength ranges [34–36]. Process route and interface chemistry differ more clearly: terminal reduction and Mg-rich white-brick firing have no simple Mediterranean analogue, while some Mediterranean lime–brick systems rely more strongly on pozzolanic brick or crushed-brick reaction [37,38]. These contrasts generate hypotheses for controlled interface testing, not categorical distinctions between traditions.

C. PROVENANCE QUESTIONS REQUIRE DIFFERENT EVIDENCE

'Where did this brick come from?' may refer to the accountable administrative unit, a specific kiln, a geological clay source, the brick's original wall position, or its exposure history. Each question requires different evidence (Fig. 5). Inscriptions may identify an official, jurisdiction, kiln owner, or craftsman, but not necessarily the clay deposit. Kiln archaeology links products to production contexts but is available for few sites. Mineral and elemental signatures can constrain compositional groups or source regions, but firing conditions and post-depositional alteration modify the analytical signal. Stratigraphic analysis and repair records, rather than chemistry alone, are needed to reconstruct placement history and identify reuse.

Provenance questions require different evidence

Question being answered	Most direct evidence	Principal limitation
Administrative producer / accountable unit	Inscription, archival quota, dated documentary record	May name the responsible jurisdiction rather than the clay source.
Specific kiln or kiln complex	Kiln-site context, marked blanks, waste, production tools	Few kilns excavated; one kiln may use multiple clays or supply several sites.
Raw-clay region or geological source	Reference clays + petrography, XRF/ICP, XRD, isotopes	Firing and alteration modify mineral and elemental signals.
Original wall placement and construction phase	Stratigraphy, bond sequence, repair records, spatial inscription pattern	Reuse and later repair can decouple find-spot from original placement.
Exposure and service history	Surface stratigraphy, salts, weathering orientation, intervention history	Usually undocumented and cannot be recovered from chemistry alone.

Triangulation strengthens attribution, but the required evidence depends on which provenance question is being asked.

FIGURE 5. Provenance is not a single variable. Evidence should be selected according to the administrative, kiln, geological, placement, or service-history question being asked.

A particularly informative example of multi-evidence triangulation is the Beijing corpus of Dong et al. [9], where inscriptions, documentary supply history, dimensions, XRF/XRD, and microstructure converge on Jiangnan and later Linqing sources. For inscriptionless bricks, Zhang et al. [39] combined XRF and XRD for 42 Ming–Qing samples and used clustering to identify regional groups. Zhu et al. [30] further showed that weathering-derived sulfate and chloride enrichment can mask original signatures, reinforcing the need to screen altered variables and sampling depths before provenance classification. Methodologically, Zhu et al. [30] is the only grouped E1 comparison in the retained corpus that explicitly evaluates weathering as a source of compositional distortion. Its design shows that provenance models should jointly assess source variation and alteration rather than treat weathering only as residual noise. Future chemometric work should treat oxide data as compositional, test mobile or contaminated elements, validate cluster stability, use grouped cross-validation by wall or kiln, and allow a specimen to remain unassigned when no reference source fits [40–42]. The binding constraint is reference coverage: documented kiln clays, unfired blanks, fired products, and, where justified, Sr–Nd isotopes are needed to translate statistical groups into places [43,44]. Supplementary Table S6 compares the principal chemometric methods and their limitations.

V. THE BRICK WITHIN THE WALL SYSTEM

Many surviving walls are asymmetric composites rather than homogeneous brick structures. E1 evidence shows brick or masonry cladding interacting with rammed-earth cores, while gates, towers, parapets, and later repairs may have different configurations. The core can supply moisture, dissolved salts, and secondary calcium to the brick from behind; Li C. et al. [6] show that outward calcium migration and carbonation can bias surface chemistry. Historical descriptions of exterior-only cladding suggest dissimilar vapour and liquid-water boundary conditions, but each configuration must be verified by phase and section rather than generalized to all walls.

Timber reinforcement is likewise site-dependent. Transmitted texts and excavations document vertical and horizontal members in selected pre-Ming and later earthen walls, sometimes leaving voids after decay [22]. Where physically confirmed, these voids may alter stiffness and moisture pathways; where inferred from texts or analogy, GPR, boreholes, or excavation are required before they enter a wall model. Tung-oil–loess, lime–organic, and sanhetu layers are best treated as putative moisture-control components until their continuity, cracking, absorption, and vapour resistance are measured.

Cladding geometry was substantial, but functional interpretation remains partly inferential. Song descriptions and the Yangzhou excavation report document battered facings, headers, stretchers, broken-brick packing, and poured lime [22,45]. Batter, bond, and slurry plausibly influence drainage, anchorage, and transport; field wetting measurements and section-scale tests are required to determine their magnitude. The interfacial transition zone (ITZ) remains a local interface even where mortar contact is extensive.

Mortars vary within and between walls. E1 studies document air-hardening lime, lime–sand, dolomitic, and organic-modified systems; sticky-rice mortar is significant but not ubiquitous [46–50]. Qi et al. [27] report a 100–200 μm ITZ in one Ming Great Wall brick–lime pair, with physical interlock and limited chemical interaction. Its thickness and chemistry are expected to vary with firing, accessible surface pores, mortar composition, moisture, and weathering, but this prediction requires replication. Preferential moisture and salt accumulation at the ITZ should likewise be demonstrated by spatially resolved measurement rather than assumed.

Assembly tests confirm that unit-level strength does not transfer directly to wall-scale strength. He P. et al. [51] measured about 1.12 MPa compressive strength and 253 MPa modulus for large Dacheng-brick masonry, while Ding [52] obtained 2.65 MPa and 405 MPa for smaller units with traditional mortar. Differences in brick format, joint thickness, mortar composition, workmanship, and test configuration all contribute; unit size alone cannot be isolated as the controlling variable. Conservation assessment must therefore address brick, mortar, interface, cladding, and wall scales separately.

VI. DETERIORATION MECHANISMS AND COUPLING

A. MOISTURE, SALTS, AND FROST

Moisture is the common enabling condition for salt transport, freezing, biological colonization, and many repair failures. Historical Chinese blue bricks store substantially more moisture than modern or handbook reference bricks, and measured properties differ among provenances [53,54]. A 600-day wall experiment showed that solid and cavity construction altered both the rate and equilibrium height of rising damp, confirming that material data must be interpreted within their assembly context [55]. Imported database values may therefore introduce substantial errors of uncertain direction in WUFI- or Delphin-type simulations unless site-specifically calibrated.

Salt damage depends on ion supply, transport, evaporation, supersaturation, nucleation, and confinement. Crystallization pressure rises with solution chemical potential and is modified by pore geometry and mechanical restraint [17,56–60]. The pore network determines where crystals can nucleate and whether pressure is relieved through connected larger pores. Chinese field studies locate sulfate and other salts near damp wall bases and weathered surfaces [10,11,61]. Accelerated tests show that Na_2SO_4, $MgSO_4$, NaCl, and their mixtures produce distinct spatial damage patterns and different levels of strength loss. Mixed-salt effects are non-additive, so rankings from single-salt tests cannot be transferred directly to field conditions [12,62]. Pre-existing mechanical damage further accelerates moisture ingress and material loss [63].

Frost damage requires saturation above a critical threshold and develops through ice expansion, hydraulic pressure, and cryosuction. Pore radius affects freezing-point depression, but critical saturation, cooling rate, salt content, drainage, tensile strength, and interfaces also matter [64]. Chinese experiments show strong moisture dependence and progressive loss of hardness, compressive strength, and modulus under cycling [65,66]. Salt crystallization and frost damage therefore share pore-confinement and moisture-supply controls but are mechanistically distinct processes.

B. CHEMICAL, ABRASIVE, AND BIOLOGICAL PROCESSES

Acidic solutions preferentially attack lime mortar: under severe laboratory conditions, mortar loses substantially more strength than the fired brick body (E2 [67]). Atmospheric sulfation is a related but still under-tested hypothesis for Chinese city wall brick (H1/E4). SO_2 deposited on damp, calcium-bearing surfaces can oxidize and form gypsum, especially where particulates catalyse the reaction [68–70]; E3). Chinese wall bricks may supply calcium through residual carbonates, Ca-bearing silicates, secondary surface calcite, and adjacent mortar. Contextual E2 evidence from the Tianning Temple Pagoda in Beijing shows surface enrichment in sulfates, nitrates, and chlorides under polluted urban exposure [71], but it does not establish the same pathway on city walls. Direct validation requires gypsum mapping against rain exposure, calcium speciation, pollutant histories, and measurement of crust vapour resistance. H1 should therefore remain visually and textually distinct from established wall mechanisms.

At arid margins, wind-driven sand abrades weakened surfaces, and antecedent frost conditioning amplifies impact damage [66]. Biological effects depend on substrate and climate. Biocrusts can protect rammed earth on dry Great Wall sectors [72,73], but this finding does not establish a protective role for lichen, moss, or endolithic colonization on fired brick under humid conditions. Conversely, microbially induced carbonate precipitation has improved crack and water-resistance indicators in Nanjing brick experiments, although reversibility, durability, and long-term field performance remain to be established [14].

C. A REINFORCING NETWORK AND A TRACTABLE MODELLING AGENDA

The deterioration mechanisms form a reinforcing network, not a linear sequence (Fig. 6). Moisture transports salts; crystallization and frost enlarge pores and cracks; roughened and increasingly connected surfaces retain more water and become more bioreceptive; mechanical pre-damage accelerates ingress; and incompatible repairs can relocate evaporation and crystallization fronts. The network is well supported conceptually, although the direction and magnitude of individual feedbacks are site- and material-dependent.

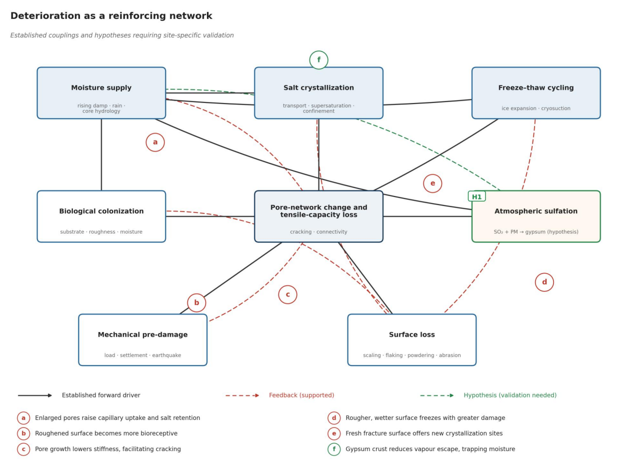

FIGURE 6. Deterioration as a reinforcing network. Black arrows indicate established forward drivers; red dashed arrows denote feedbacks supported by direct or transferable evidence; the green H1 path denotes atmospheric sulfation, a synthesis-generated hypothesis requiring site-specific validation.

A useful coupled model must resolve multiple scales and domains: brick pore network, mortar/ITZ, cladding, rammed-earth core, cracks, and environmental boundaries. Hydraulic and thermal transport should be coupled to ionic advection–diffusion and phase equilibrium, and subsequently to crystallization or ice pressure and damage-dependent permeability. The framework proposed here is a research architecture, not a validated model. Supplementary Table S7 defines the minimum domains, constitutive relations, parameter requirements, validation stages, and two dimensionless experiment-design indices at the representative-elementary-volume scale. Calibration should proceed sequentially—moisture transport, reactive salt transport, and only then mechanical damage—with independent field validation and explicit uncertainty analysis [75–77].

Climate change adds a shifting boundary condition. Response-based risk analysis is preferable to air-temperature indices alone because damage depends on material moisture and phase state [78–80]. Because Chinese walls span arid, cold, monsoonal, and polluted urban climate zones, risk maps should be provenance- and assembly-specific rather than based on national averages.

TABLE III. Mechanisms, Evidence Status, Controlling States, and Immediate Conservation Implications

Mechanism	Controlling state or pathway	Representative evidence	Immediate implication
Rising damp / rain	Moisture storage, capillary conductivity, joints, core boundary	E1: Li Y.H. et al. [53,55]; Zhao J.H. et al. [54]	Measure wall- and material-specific hygric functions before simulation or sealing.
Salt crystallization	Ion load, evaporation front, pore confinement, pre-damage	E1/E2/E3: Han et al. [11]; Zhang J.K. et al. [12]; Ma et al. [63]	Identify salts and moisture source; avoid single-salt extrapolation.
Freeze–thaw	Critical saturation, pore size, cooling, drainage, salts	E2/E3: Yue et al. [65]; Hao et al. [66]	Control water supply and validate cycles against local climate.
Acid / sulfation	Mortar chemistry, surface Ca, SO_2, particulates, wetting geometry	E2/E3; H1=E4: Chen et al. [67]; Böke et al. [68]; Fodde [74]	Treat gypsum formation on Chinese wall brick as a testable hypothesis.
Abrasion	Wind-sand energy and prior frost/salt weakening	E2: Hao et al. [66]	Assess coupled exposure, not abrasion resistance alone.
Biological action	Substrate, roughness, moisture, climate, community	E1/E2: Cao et al. [72]; Mu et al. [14]	Distinguish fired brick from earthen biocrust; require long-term field evidence.

VII. DIAGNOSIS AND CONSERVATION

A. DIAGNOSIS FROM UNIT TO WALL

Non-destructive methods yield proxy indicators rather than direct strength measurements. Rebound number, ultrasonic pulse velocity, SonReb, and microdrilling require calibration to the specific material population and moisture state [35,81]. Chinese studies show that locally calibrated combined methods outperform a single index, whereas generic curves can under- or over-predict historical-brick strength [82,83]. Strength assessment remains essential for structural safety, but it does not substitute for hygric or pore-network characterization when durability is the concern.

At wall scale, GPR has resolved internal voids, core-cladding separation, and moisture-related anomalies on the Beijing Great Wall [84]. UAV photogrammetry, terrestrial laser scanning, and machine vision support repeatable surface mapping, inscription recording, vegetation detection, and spalling classification [2,85–87]. Their value depends on consistent labelling, uncertainty reporting, cross-site validation, and systematic linkage to physical samples and intervention records. A geometric model that lacks moisture, salt, damage, and treatment-history data remains an inventory rather than a predictive digital twin.

B. MATERIALS COMPATIBILITY AND PREVENTIVE INFORMATION

Treatment selection must balance liquid-water exclusion, vapour permeability, salt redistribution, penetration depth, colour change, reversibility, and long-term ageing. On Nanjing wall bricks, organosilicons differed substantially in penetration, water repellency, vapour permeability, and salt-cycle performance; partial treatment created vulnerable hydrophilic–hydrophobic boundaries on certain brick substrates [13]. Nanolime and other nanomaterial consolidants can enhance near-surface cohesion, but their performance depends on substrate porosity, delivery method, carbonation kinetics, and field exposure conditions, so laboratory gains should not be generalised without multi-year field trials [88].

Replacement brick and mortar should be compatible as a system. WW/T 0049–2014 already addresses strength, density, absorption, frost, and efflorescence. A future revision should investigate operational pore-network and drying-compatibility criteria rather than merely adding “pore size” as an undefined requirement. The necessary programme includes interlaboratory comparison of MIP, NMR, and transport tests; explicit distinction between pore-body and pore-throat metrics; repeatability and sampling requirements; repaired-assembly tests; and climate- or exposure-specific acceptance bands. Mechanical requirements should be retained. Mortar selection should match binder chemistry, aggregate, vapour and liquid transport, soluble salts, stiffness, and adhesion; reliance on a single “original mortar” composition is unreliable where construction and repair phases differ [50,89]. Repaired assemblies should be evaluated for ITZ formation and moisture redistribution, not solely constituent strength.

Effective preventive conservation requires information continuity across project cycles. EN 16096:2012 [90] separates periodic condition survey from specialist diagnosis, while ISO 19650-1:2018 [91] and ISO 19650-3:2020 [92] define information requirements, exchange, version control, and operational stewardship. Applied to city walls, a realistic hierarchy is wall network, section, monitored zone, sampled brick/mortar/ITZ, intervention record, and decision record. Representative sampling is more feasible than unit-level characterization of millions of bricks. Survey data, laboratory results, repair records, uncertainty, and subsequent performance must remain linked across projects. Supplementary Table S8 describes the information layers and stewardship requirements.

VIII. SYNTHESIS, PRIORITIES, AND CONCLUSIONS

A. INTEGRATED INTERPRETATION

The evidence supports a whole-life-cycle interpretation incorporating four feedback mechanisms. Repair can alter the moisture and vapour balance it was intended to correct. Salt crystallization, frost action, and chemical attack progressively degrade joints and interfaces, so the masonry tested today differs from the assembly as originally constructed. Weathering progressively rewrites the pore network that is subsequently measured and reported as an ‘original’ property. Reuse transfers accumulated damage and salt loading from one service environment to another. These feedbacks explain why production history, provenance, present condition, and conservation requirements cannot be analysed in isolation.

Three conclusions follow. First, pore-network and transport characteristics are central durability mediators but are not sufficient alone; strength, tensile capacity, salts, drying, interfaces, and assembly geometry remain necessary (supporting P1). Second, the current property corpus is too heterogeneous for pooled constants, and missing methodological information cannot be repaired by statistical assumptions (supporting P2). Third, administrative provenance, geological source, construction placement, and exposure history are distinct attributes that demand different evidence (supporting P3).

B. SIX RESEARCH PRIORITIES

TABLE IV. Dependency-Based Priorities for the Next Phase of Research

Priority	Near-term deliverable	Why it matters / dependency
1. Harmonized reporting and open data	Minimum information standard; specimen-level repository; direct/context/reference tagging	Precondition for comparison, model calibration, and standards revision.
2. Kiln, source-clay, and refiring references	Paired clay-blank-fired products from documented kilns; temperature-atmosphere series	Separates raw-material, firing, and alteration effects; anchors provenance.
3. Interface and repaired-assembly testing	Micro-CT/SEM/nanoindentation across brick–mortar pairs; section-scale moisture and salt tests	Moves compatibility from isolated units to ITZ, cladding, and wall behaviour.
4. Long-term monitoring and climate risk	Moisture, temperature, salt, and intervention time series across height, aspect, and climate zone	Provides boundary conditions and independent validation for deterioration models.
5. Provenance with reuse explicitly represented	Reference database, compositional-data workflow, stratigraphy and repair-history integration	Prevents find-spot from being misread as source or exposure history.
6. Coupled models and information continuity	Staged H → HC → THCM models linked to survey, diagnosis, intervention, and versioned records	Converts monitoring into decisions while preserving uncertainty and minimum intervention.

The complete 16-gap register, its evidence status, dependency, and mapping to the six priorities is provided in Supplementary Table S9.

C. LIMITATIONS AND CONCLUSION

This review is limited by the small direct corpus, uneven reporting, and the imbalance between Chinese case evidence and English-language theory. It is integrative rather than exhaustive; the iterative search was not protocol-registered and raw database hit counts were not preserved. The 2025–2026 literature is still evolving, and online-first metadata require checking at submission. The historical corpus overrepresents official and strategically important walls, while pre-Ming material evidence remains sparse. The coupled framework is a multiscale research specification rather than a solved or validated model, and H1 atmospheric sulfation is a falsifiable hypothesis rather than an established city-wall mechanism. Evidence codes make these limits explicit, but they do not eliminate uncertainty in source translation, site attribution, or transfer from contextual materials.

Ancient Chinese city wall bricks have been studied intensively but not yet as one material–history system. The most productive transition is from isolated characterization toward comparable data, source-calibrated firing interpretation, interface and assembly testing, coupled field validation, and information that survives beyond a single repair project. Conservation practice should neither select replacement bricks by strength alone nor replace strength with a single pore metric. It should specify a compatible material and assembly state, document the evidence and uncertainty supporting that specification, and verify performance over time.

. DATA AVAILABILITY

No new primary experimental data were generated. The evidence maps, coding rules, methodological tables, and research-gap register supporting this review are provided in the Supplementary Material.

. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During preparation of this manuscript, the authors used OpenAI GPT-5.4 to assist with language editing, structural revision, and reference-checking. The authors reviewed and edited all outputs and take full responsibility for the content of the article.

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SUPPLEMENTARY MATERIAL

This supplement documents the search strategy, evidence-role coding, direct-study corpus audit, quantitative property evidence, minimum reporting standard, provenance analytics, coupled-modelling requirements, preventive-conservation information hierarchy, complete research-gap register, and the corpus-coding matrices underlying Fig. 2. Tables S1–S10 provide the auditable basis for the main-text synthesis. E1 denotes direct object-specific evidence, E2 contextual Chinese heritage evidence, E3 transferable mechanisms, methods, and normative frameworks, and E4 synthesis-generated hypotheses.

S1. SEARCH STRATEGY AND CORPUS FORMATION

TABLE S1. Database-Specific Search Blocks, Update Date, and Retained Corpus

Source	Search block or procedure	Last updated	Retained role / count
CNKI, Wanfang, VIP	(城墙砖 OR 明城墙砖 OR 长城砖 OR 古青砖 OR 铭文砖) AND (材料性能 OR 产地 OR 窑址 OR 烧成 OR 灰浆 OR 盐害 OR 冻融 OR 无损检测)	12 Jul 2026	E1 and E2; Chinese case, historical, and technical evidence
Web of Science and Scopus	TITLE-ABS-KEY: (China* OR Ming OR Great Wall OR city wall) AND (brick OR qingzhuan OR grey/blue/white brick) AND (XRF OR XRD OR SEM OR MIP OR provenance OR mortar OR salt OR frost OR conservation)	12 Jul 2026	E1–E3; indexed scholarship
ScienceDirect, SpringerLink, Taylor & Francis	Targeted title/abstract searches for city-wall brick, firing, lime mortar, ITZ, rising damp, salts, NDT, and conservation compatibility	12 Jul 2026	Publisher verification and full-text follow-up
Google Scholar and publisher sites	Backward/forward citation tracking; author and title verification; recent online-first checks	12 Jul 2026	Recall expansion and bibliographic verification
Final retained corpus	Iterative integrative selection; raw hit/exclusion counts were not preserved and are not retrospectively reconstructed	—	93 sources: 25 Chinese-language and 68 English-language; E1=40, E2=11, E3=42; E4 hypotheses not counted

Eligibility required primary data, a directly relevant historical or archaeological dataset, a mechanistic model, or a normative framework. Duplicate reports, promotional material, modern-brick studies without a heritage comparator, and site descriptions without technical or institutional evidence were excluded. Because the search evolved iteratively across disciplines, raw hit and exclusion counts were not consistently preserved and are not reconstructed retrospectively. The review is transparent about its final corpus and coverage rationale but does not meet the exhaustiveness criterion of a protocol-registered systematic review (e.g., PRISMA [19]).

S2. EVIDENCE STATUS AND TRANSFERABILITY

TABLE S2. Evidence-Role Coding Used in the Main Text

Code	Definition	Typical examples	Permitted inference
E1	Direct evidence from Chinese city walls, Great Wall sectors, or documented brick/mortar supply systems	In situ or curated city-wall samples; inscriptions; kiln products; wall-scale monitoring	Directly supports object-specific statements, subject to site and sampling limits
E2	Contextual evidence from other Chinese historical bricks, masonry, kilns, or earthen heritage	Pagoda bricks, floor bricks, reconstructed masonry, biocrust on earthen walls	Supports comparison or mechanism transfer; cannot be generalized without validation
E3	Transferable mechanisms, methods, or normative frameworks not tied to a single city-wall material population	Ceramic petrology, salt/frost theory, generic Chinese mechanism studies, NDT methods, RILEM/EN/ISO guidance	Supports mechanistic interpretation or method design; requires object-specific validation
E4	Hypothesis or prediction generated by this review	Atmospheric sulfation H1; site-dependent timber-void effects; interface predictions	Defines a falsifiable research question; must not be presented as established fact

S3. DIRECT ANALYTICAL AND DIAGNOSTIC CORPUS AUDIT

TABLE S3. Twenty-Five Direct Analytical or Diagnostic Studies Coded by Primary Site Focus and Status

Study	Primary site(s)	Primary contribution	Status code	Cluster used for bias

				audit
Shi et al. [7]	Nanjing, Xi’an, Linqing, Beijing Great Wall	Cross-regional material comparison	High-status / strategic	Core cluster
Shi et al. [8]	Same multi-site corpus	Pore network and method comparison	High-status / strategic	Core cluster
Shi et al. [28]	Nanjing wall	White-brick refiring	Imperial capital	Core cluster
Chun et al. [32]	Yichun–Nanjing supply	White-brick properties and source	Official supply	Core cluster
Li C. et al. [6]	Xi’an wall	Mineralogy and microstructure	Prefectural / strategic	Core cluster
Gao and Sun [29]	Xi’an barbicans	Physical and mineral properties	Prefectural / strategic	Core cluster
Jin et al. [61]	Xi’an wall	Surface weathering	Prefectural / strategic	Core cluster
Dong et al. [9]	Beijing wall / Linqing references	Provenance and performance	Imperial capital	Core cluster
Zhu et al. [30]	Four Beijing-area sites	Multi-site compositional grouping with explicit weathering assessment	Capital / major heritage	Core cluster
Wang et al. [83]	Beijing Ming brick	SonReb calibration	Imperial capital	Core cluster
Dettmering and Dai [50]	Ming Great Wall	Lime-binder typology	Strategic frontier	Core cluster
Qi et al. [49]	Dazhuangke Great Wall	Ancient mortar evolution	Strategic frontier	Core cluster
Qi et al. [27]	Ming Great Wall	Brick–lime ITZ	Strategic frontier	Core cluster
Qian et al. [84]	Beijing Great Wall	GPR internal defects	Strategic frontier	Core cluster
Han et al. [11]	Pianguan wall	Brick deterioration and salts	Strategic frontier	Core cluster
Wu et al. [85]	Nanjing wall	UAV/TLS defect mapping	Imperial capital	Core cluster
Yuan et al. [86]	Nanjing wall	AI vegetation/spalling detection	Imperial capital	Core cluster
Yang et al. [13]	Nanjing wall brick	Organosilicon treatment	Imperial capital	Core cluster
Mu et al. [14]	Nanjing wall brick	MICP repair	Imperial capital	Core cluster
Liu and Zhang [10]	Pingyao wall	Material and weathering mechanisms	County city	Outside core cluster
Xiao et al. [48]	Wugang wall	Sticky-rice lime mortar	Regional city	Outside core cluster
Qian et al. [89]	Xindeng wall	Mortar heterogeneity	Local city	Outside core cluster
Yue et al. [87]	Kaifeng wall	Image-based weathering index	Regional centre	Outside core cluster
Zhang et al. [39]	Multi-origin inscriptionless bricks	Chemometric provenance	Mixed / uncertain	Outside core cluster
Liu et al. [47]	Seven Ming–Qing walls	Mortar survey	Mixed hierarchy	Outside core cluster

Nineteen of the twenty-five studies (76%) were coded as primarily focused on Nanjing, Xi’an, Beijing/Linqing, or major Great Wall sectors. The coding is descriptive rather than a value judgement: these sites are analytically important, but their concentration limits generalization to county-grade or locally produced brick.

S4. QUANTITATIVE PROPERTY EVIDENCE MAP

TABLE S4. Quantitative Property Evidence Map; D=Direct, C=Contextual, R=Reference

Source / site	Density ($g\ cm^{-3}$)	Water absorption (%)	Porosity (%)	Compressive strength (MPa)	Reference
D: Xi’an City Wall, Ming	~2.02	12.82–14.12	—	10–12	Li C. et al. [6]
D: Xi’an City Wall, Qing	~1.80	12.82–14.12	—	10–12	Li C. et al. [6]
D: Xi’an barbican gates	1.81–1.88	14.26–18.33	19.31–21.63 (open)	10.67–11.98	Gao & Sun [29]
D: Beijing city wall (Fengtai)	1.62 (mean)	—	—	8.2–24.7 (mean 15.9)	Dong et al. [9]
D: Beijing-area multi-site	varies; Ming GW ~1.65	varies; Ming GW ~20.9	not harmonized	not uniformly reported	Zhu et al. [30]
R: Linqing reference bricks	1.44–1.67	—	—	7.6–25.4	Dong et al. [9]
D: Beijing Yanqing city brick	1.69	—	—	27.0	Dong et al. [9]
C: Kaifeng heritage blue brick	1.64	17.86 (24 h)	20.99 (open)	11.82	Ma et al. [93]
C: Kaifeng heritage blue brick	1.627	20.52 (24 h)	3.36 (void ratio)	11.82	Ma et al. [63]
C: Lanzhou (Baiyi Pagoda area)	1.58	20.53	34.64 (open); 45.33 (total)	20.73	Zhang J.K. et al. [12]
C: Inner Mongolia (unfrozen)	2.10	1.72	—	11.68	Hao et al. [66]
C: Jiangnan blue brick	1.70	11.8	—	19.51	Chen et al. [67]
R: "Typical old brick", China	—	—	—	10.0–15.7 (normalized)	Zhao et al. [25]

These values are preserved as an evidence map. They do not convert non-equivalent geometries, moisture states, pore metrics, or direct and indirect strength estimates into pooled constants.

S5. MINIMUM REPORTING STANDARD

TABLE S5. Minimum Information for Historical-Brick Characterization

Domain	Minimum information	Why it matters	Status if absent
Identity and provenance	Unique ID; current wall and position; brick type; chronological basis; inscription, kiln, or reuse	Separates administrative origin, find-spot, date, and	Contextual narrative only

	evidence	service history	
Sampling and condition	Height, aspect, depth, weathering, salts, prior treatment, intact/friable selection	Distinguishes initial material features from service-induced change and sampling bias	Do not generalize to the wall population
Specimen geometry	Cut/core/whole unit; dimensions; h/d; loading orientation; surface preparation	Strength and transport results are size- and direction-dependent	Do not pool across geometries
Conditioning and test	Drying/saturation protocol; standard; device; loading rate; calibration and corrections	Defines the estimand and enables replication	Stratify by method or exclude
Pore and hygric definitions	Open/total/MIP-accessible porosity; method and size domain; absorption duration; vapour and drying method	Prevents non-equivalent quantities from sharing one column	Narrative comparison only
Statistics and linkage	n; individual values; mean and SD; exclusions; linked IDs across XRF/XRD/MIP/mechanical tests	Quantifies uncertainty and enables multilevel synthesis	No meta-analysis or correlation

S6. PROVENANCE ANALYTICS

TABLE S6. Chemometric Methods and Limitations for the Present Corpus

Method	Requires k a priori	Compositional closure	Cluster geometry	Rejects unknown source	Principal risk / use
PCA (visualization)	No	Only after clr	—	No	clr-PCA supports interpretation; raw-oxide PCA can be dominated by closure and high-variance oxides.
k-means	Yes	Use ilr/pivot coordinates	Spherical, similar variance	No	Useful exploratory partition, but sensitive to scaling, initialization, and forced assignment.
Hierarchical clustering	No	Aitchison distance or ilr	Depends on linkage	No	Topology depends on linkage; uncertainty and probabilistic assignment are absent.
Gaussian mixture	Selected by model criterion	Use ilr	Elliptical, variable covariance	Partial, via low posterior	Parameter-rich relative to current sample sizes; covariance estimates may be unstable.
DBSCAN / HDBSCAN	No	Use ilr	Arbitrary	Yes, noise label	Noise denotes compositional outliers, not reuse itself; results depend on density and scaling parameters.
LDA	—	Use ilr	Linear boundaries	No	Requires labelled classes and stable covariance; small, correlated datasets risk overfitting.
SVM / random forest	—	Use ilr or validated features	Flexible	No by default	Needs reliable labels and grouped cross-validation; feature importance does not establish causation.
One-class SVM / conformal prediction	—	Use ilr or validated features	Flexible	Potentially, with calibration	Promising open-set framing, but needs independent calibration, exchangeability checks, and adequate reference classes.

Sample-size cautions are risk indicators rather than universal thresholds. Method choice should be justified by class structure, label quality, dimensionality, reference coverage, and grouped validation.

S7. COUPLED MODELLING REQUIREMENTS

TABLE S7. Minimum Domains, Evidence, and Validation Requirements for Coupled Modelling

Domain / scale	Processes and state variables	Evidence presently available	Principal unresolved requirement
Brick pore network / REV	Moisture storage and transport; salt and ice phases; cracking; evolving properties	MIP/NMR/adsorption, sorption, absorption, drying, salt and freeze–thaw tests for selected provenances	Harmonized linked datasets and damage-dependent transport functions
Brick–mortar ITZ / interface	Penetration, adhesion, local chemistry, preferential transport, debonding	One detailed Ming Great Wall ITZ study plus mortar characterization	Replicate the reported 100–200 µm ITZ [27] across brick, mortar, repair, and deterioration states
Mortar and core / wall section	Reservoir/source terms; asymmetric drying; dissolved salts; cracks and voids	Selected mortar chemistry, rising-damp experiments, GPR imaging	Field-calibrated core–cladding moisture and salt fluxes
Surface / environment	Rain, evaporation, temperature,	Climate records, surveys, accelerated exposure studies	Exposure-resolved boundaries and direct sulfation/bioreceptivit

	pollutants, crusts, biota, abrasion		y measurements
Decision scale	Coupled response, uncertainty, service risk, intervention scenarios	Case studies and emerging monitoring tools	Multidomain validation and uncertainty quantification before predictive use

Experiment-design indices are defined at a representative-elementary-volume scale. The crystallization damage number $\Pi c = b\varphi c Pc/ft$ is dimensionless, where b is an effective-stress/Biot coefficient (dimensionless), φc is the connected pore fraction occupied by crystal (dimensionless), Pc is crystallization pressure (Pa or MPa), and ft is local tensile strength in the same pressure units. The advective Damköhler number Da = kL/U is dimensionless, where k is an effective first-order reaction rate (s^{-1}), L is transport length (m), and U is characteristic pore-water velocity (m s^{-1}). When diffusion dominates, $kL^2/Deff$ is the appropriate form, with Deff in m^2 s^{-1}. Every quantity must be calibrated for the domain and scale being modelled.

S8. INFORMATION CONTINUITY

TABLE S8. Information and Stewardship Layers for Preventive Conservation

Information level	Primary spatial unit	Core data	Purpose and update
Wall network	City or Great Wall section	Location, significance, climate zone, responsibility, hazard screening	Strategic prioritization; update after major survey or hazard change
Wall segment	Construction and exposure unit	Geometry, cladding, aspect, drainage, visible condition, repair phases	Periodic comparable survey; EN 16096 separates survey from diagnosis
Representative monitoring zone	Instrumented or repeatedly imaged area	Temperature, moisture, salts, GPR/NDT, defect maps, fixed photography	Trend detection and model calibration; continuous or scheduled update
Sample and interface	Selected brick, mortar, ITZ, core, or crust	Provenance, XRF/XRD, pore network, hygric/mechanical properties, condition	Mechanism and compatibility evidence; update when sampled
Intervention and outcome	Defined treatment area	Material batch, specification, application, acceptance data, follow-up	Learning from repair; ISO 19650 principles support versioned exchange and custody
Decision record	Risk or intervention case	Evidence, uncertainty, significance, alternatives, minimum-intervention rationale	Auditable support; update at each decision point

S9. EXPANDED RESEARCH-GAP REGISTER

TABLE S9. Sixteen Research Gaps Mapped to the Six Main-Text Priorities

No.	Gap	Required evidence or deliverable	Main-text priority
1	Non-comparable property data	Harmonized geometry, moisture, pore metric, raw values, uncertainty	1
2	Durability specification	Interlaboratory pore-network, drying, transport, and assembly-compatibility criteria	1 / 3
3	Brick–mortar ITZ	Cross-material microstructure, chemistry, transport, and ageing	3
4	Core–cladding interface	Embedded moisture/salt/temperature monitoring and GPR	3 / 4
5	Inscriptionless provenance	Source-clay references, compositional workflow, grouped validation, rejection option	2 / 5
6	Firing regimes	Controlled refiring and instrumented traditional-kiln trajectories	2
7	Replacement systems	Test repaired assemblies, not constituents alone	3
8	Long-term field monitoring	Multi-season, multi-height state-variable time series	4
9	Climate risk mapping	Material-response simulations by climate zone and provenance	4 / 6
10	Biodeterioration vs bioprotection	Substrate- and climate-specific bioreceptivity criteria	4
11	Corpus bias and reuse	County-grade sampling plus stratigraphic/documentary reuse controls	5
12	Timber voids and revetment layers	Site verification, mapping, hygric and structural characterization	3 / 4
13	Atmospheric sulfation H1	Gypsum mapping, Ca speciation, crust transport, urban–rural comparison	4
14	Coupled modelling	Staged hydraulic, reactive-transport, and mechanical validation	6
15	Preventive information system	Persistent linkage of survey, sample, intervention, and outcomes	6
16	Pre-Ming material continuity	Comparable Han–Song–Yuan samples and chronology-controlled testing	2 / 5

Dependencies are qualitative and should be revisited as access, datasets, and methods change. Gaps 1–4 are foundational; Gaps 5–9 and 13–14 are mechanism and prediction programmes; Gaps 10–12, 15, and 16 require broader disciplinary or institutional collaboration.

S10. CORPUS CODING UNDERLYING FIG. 2

TABLE S10a. Publication Language by Evidence Role for the 93 Retained Sources

Publication language	E1	E2	E3	Total
Chinese-language	17	4	4	25
English-language	23	7	38	68
Total	40	11	42	93

TABLE S10b. Primary Research Theme by Evidence Role for the 93 Retained Sources

Primary research theme	E1	E2	E3	Total
Historical context, institutions, and manufacture	11	1	0	12
Materials, firing, and pore network	6	3	4	13
Provenance and analytical methods	4	0	5	9
Mortar, interface, and masonry	6	3	2	11
Deterioration, moisture, and climate	6	3	22	31
Diagnosis, conservation, and information	7	1	9	17

Coding note: each retained source was assigned one publication-language category, one evidence role, and one primary research theme for Fig. 2. The primary-theme code is intentionally non-overlapping for visualization and does not imply that a source contributes to only one section of the review.