CHEMISTRY AND MATERIALS SCIENCE FOR CULTURAL HERITAGE: APPLICATION IN THE HISTORIC CONSTRUCTION MATERIALS AREA

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Abstract. *Historic construction materials behave as reactive, multiscale systems whose long-term stability is determined by coupled chemical, physical, and biological processes. This review synthesizes advances in analytical chemistry and materials science for the conservation of stone, brick, and mortars, with emphasis on mineral-compatible strategies. Developments in analytical methods (including completely non-invasive techniques) and the rise of data fusion and machine learning allows the proposal of new alternative, aligned with predictive diagnostics. Literature data, regarding both laboratory-level tests and field studies evidence the need for sustainable, fully compatible and efficient solutions. The present work also constitutes an argument for standardization and FAIR data, to enable comparability across projects, and studies, as well as a short description of the path ahead, toward predictive conservation.*

Keywords: Cultural heritage conservation; analytical methods; predictive conservation

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1. Introduction

Historic buildings are not silent witnesses of the past, they must also be regarded as slowly changing materials, which can be analyzed from a chemical perspective to present the changes and alteration during their lifetime. Stones can expand or contract with every change of season or temperature, mortars carbonate and recarbonate, while surfaces are affected by the minerals' transformation in response

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to external factors [1]. Over centuries, this quiet mix of dissolution, recrystallization, and transformation becomes both their beauty and their vulnerability. To conserve such materials should be regarded not as an attempt to stop the decay, but of understanding its rhythm, and its deeper meaning.

Whether we speak of a cathedral wall or a Renaissance façade, the elements of built heritage do not represent a fixed artifact, but an evolving system. Its structure contains several layers of materials that can be hardly distinguishable by the untrained human eye, from nanometer-thin hydration layers and amorphous films on grain boundaries to massive stone blocks. At each of these scales, interactions unfold continuously: water condenses and evaporates, ions migrate, minerals grow and dissolve, microorganisms colonize and retreat. What we call "decay" is, in truth, a complex equilibrium. To care for such materials is not just an act of intervention or repair, but an understanding of the complex phenomena involved, which makes the heritage not static matter, but a "living" and evolving system [2].

During the last decades, we can witness a major shift in the conservation of built heritage, from more of an artisanal practice, into what is now called "heritage science" - science of materials under ethical constraint. Chemists, engineers, physicists, and conservators started to work together on a common ground, that connects atomic-scale processes to structural performance: the hydration of portlandite and the endurance of arches, the phase transitions in lime mortars and the mechanical behavior of masonry vaults. The mid-20th century brought laboratory chemistry, focusing on what was visible - salt efflorescence, black crusts, pigment fading. But only in the last few decades has the field embraced the full system: the chemical, physical, and biological processes that make heritage both vulnerable and a continuously changing system. In our days, conservation no longer ends with the visible stabilization of the surface, but it begins with understanding the complex interactions within the material itself [3, 4].

This transformation was driven by the advancement in analytical chemistry and materials science. Fourier-transform infrared spectroscopy (FTIR) can trace the slow carbonation of mortars and the signatures of sulfate attack. Scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM–EDX) can reveal how consolidants bond (or fail to bond) to ancient substrates, while Raman spectroscopy can be used to distinguish the crystalline signatures of gypsum, calcite, or oxalate. And these methods are only a part of what specialists in heritage science today are working with. Using complex analytical protocols, every façade analyzed becomes not just an object, but a landscape of reactions - dynamic, interconnected, and site-specific.

The European research landscape (especially driven by the Horizon Europe and Joint Programming Initiative on Cultural Heritage frameworks) contributed to this modernization of the heritage science approach. Collaborative efforts have merged natural sciences with conservation ethics, yielding new generations of mineral-compatible consolidants. Systems based on nanolime, hydroxyapatite, and hybrid silicate–carbonate formulations are now designed to be completely compatible with the stones they protect [5-7]. The modern conservation/ restoration materials are not meant just to cover the original substrate, but to coexist - creating a state of stable dialogue between the ancient and the new.

The present work does not attempt to assemble an inventory of materials or techniques, but to trace the logic that connects chemistry to cultural continuity. It explores how analytical methods have deepened our understanding of degradation, how we can read and understand the stone, brick, or mortar, and how interventions can respect the physical, chemical, and ethical integrity of historic materials.

2. Historic construction materials: composition, microstructure, and provenance

To preserve a building, the first step should be its exact understanding as a composite material system, stratified, porous, reactive, and in continuous “dialogue” with the surrounding environment. Every component (either if we are speaking of stone, brick, mortar, or plaster) bears its own chemical memory. Together, they form the heritage ecosystem, an intricate interplay of mineralogy, moisture, and time.

2.1. Stone materials and heterogeneity

At a first glance, natural stone appears simple and inert, a solid witness to the centuries it has endured. However, beneath this apparent simplicity lies a great complexity. What seems immutable is, in truth, a network of minerals in constant negotiation with water, air, and light. The same stone that shapes cathedrals and palaces is, at the microscopic level, a complex mosaic of crystals, pores, and other characteristics that are in strong connection with its origin. Limestone, marble, and sandstone, the most important materials from the European architecture - may look alike in the hands of a mason, yet each presents enormous variability. No two quarries yield the same stone and no two blocks age alike, even when found within the same wall. Every layer of the stone presents a distinct response to pressure, chemistry, and time. Within the different layers of the stones lie subtle impurities (such as minor traces of clay, pyrite, feldspar, or organic matter) that influences the stone’s behavior and fate. A fraction of iron turns pale calcite ochre, a film of clay redirects water flow, while an inclusion of pyrite becomes a future blister of rust [8].

Limestone, built mostly of calcite ($CaCO_3$), contains in its structure, the evidence of ancient seas and shells, while dolomitic varieties, richer in magnesium

($CaMg(CO_3)_2$), weather differently (slower under acidic rain, more brittle under frost). The porosity of the stones also has a great influence on the materials behavior, as moisture and salts can migrate, or crystals grow, in a close connection with the general porosity [9].

With sandstone, the associated problems can become even more complicated. A sandstone may be cemented by quartz, by iron oxides, or by calcite, and each variant behaves differently. Siliceous sandstones can endure centuries of rain, yet their rigidity can turn into a threat under stress. Iron-rich sandstones darken, as Fe^{2+} turns to Fe^{3+} in humid air, giving façades their familiar patina. Clay-bound sandstones, on the other hand, live with the seasons — swelling when it rains, shrinking when the sun returns, until the smallest crack turns into loss. These are not flaws of the materials, but natural pathways strongly connected with their chemistry [10]. For the conservator, understanding such individuality represents a necessity. To propose a treatment only by considering the stone, without understanding its inner structure, represents a threat as big as not making any intervention at all.

Every stone also tells a story beyond its chemistry. Its trace elements signature can be used to identify the quarry it came from, which, in turn, can be used not only for provenance studies, or mapping ancient trade routes, but also to deeply understand the stones' behavior and proposal of the appropriate consolidant treatment. No stone is generic, as each carry within its crystalline structure a unique path toward weathering, and to understand this is the first step in the scientific approach of the preservation [8].

2.2. Bricks, ceramics, and fired materials

Bricks are, at their essence, earth reborn through fire. Each one carries within it the characteristics of the production process, from the mineral nature of the clay used, to the temperature used. The analytical analysis of a brick reveals a true record of its chemistry. Between 700 and 900 °C, minerals such as kaolinite and illite lose their structural water, transforming into metakaolin and the first traces of glassy matter. As the fire temperature is raised above 1000 °C, new crystalline phases can be encountered, for examples mullite and silicate glass, which have the role of sealing pores and hardening the matrix [11].

However, as most man-made materials, the bricks production process can have imperfections, which gives particular artifacts their individuality. One of the reasons for the occurrence of such imperfections is represented by the ancient kilns, themselves, which were not uniform. Temperature gradients, variable oxygen levels, and uneven airflow made each firing different. As such, within a single wall, one brick may be dense and glassy, another soft and porous, depending on its position in the kiln [12]. This mosaic of phase composition and porosity defines how the structure breathes, absorbs water, and withstands centuries of rain, frost, and salt. To conserve historic brickwork, one must read these traces as evidence - to reconstruct not just what the brick is, but how it became itself.

Modern analytical techniques contributed to a better understanding of the nature of the artifacts. The content of glassy phases determines the brick's resistance to frost, while the distribution of pores influences how water and salts move through it [13]. Historical bricks, which were typically fired at lower and more irregular temperatures, tend to possess a more open, interconnected porosity, which allows moisture to move through the structure, but also makes them more vulnerable to salt crystallization and freeze–thaw fatigue. When designing mortars or consolidants for their repair, the quest is to match this porosity, and not to surpass it, as a treatment too dense or too rigid can negatively influence the material, forcing stresses to concentrate and forming new cracks.

Other issues (and more complicated) are raised when reaching the ceramic architectural elements, such as terracotta ornaments, sculpted friezes, and glazed tiles. These, by their nature, represent hybrid materials, where clay and glaze coexist in delicate equilibrium. The glaze–body interface represents a region of tension, both mechanical and chemical [14, 15]. Differences in thermal expansion can make the glaze separate from the substrate, while glazes rich in lead or alkalis, once prized for their luminous color, are now prone to leaching and weathering. The conservator's task is therefore not only to preserve form and color, but to stabilize a fragile chemical balance, which in itself represents an attempt to prevent a microscopic mismatch from affecting centuries of craftsmanship. In studying such materials, it is important to keep in mind that bricks and ceramics are not inert artifacts, they represent dynamic systems, continuing to respond to the surrounding environment [2].

2.3. Mortars and plasters

Mortars and plasters represent the indispensable connectors that hold walls together. However, they must be regarded as more than passive binders between stones and bricks, as they mediate moisture exchange, buffer temperature and humidity changes, and accommodate subtle structural movements [16]. Traditional lime mortars begin with slaked lime, calcium hydroxide, $Ca(OH)_2$, that was soft enough to be troweled yet reactive enough to reconstitute itself into stone. When exposed to atmospheric carbon dioxide, it undergoes carbonation, transforming into calcium carbonate, $CaCO_3$. This transformation' kinetics is influenced by several factors, including pore geometry, ambient humidity, and temperature. In fine-pored mortars, carbonation may take years to complete, while in open-textured ones, it can proceed rapidly but unevenly, creating hardened crusts that mask softer interiors [17].

The addition of pozzolanic materials (volcanic ash, finely ground brick, or silica-rich dusts) introduces another layer of complexity. These additions bring silica and alumina into the mix, reacting with lime to form calcium silicate hydrates and calcium aluminate hydrates), the same types of compounds that confer strength to modern cements, yet here produced through slower, self-regulating reactions. The result is a hydraulic mortar, capable of setting even under damp conditions, with early strength and improved resilience [18]. The Romans mastered this chemistry long before it was named: their volcanic pozzolanas created mortars that not only set under water but are still viable today. Each pozzolana contributes its own fingerprint, some enhancing strength, others improving permeability or resistance to sulfates, the final result being not a uniform binder but a complex mixture of crystalline and amorphous areas, slowly evolving toward equilibrium.

Over time, these systems do not remain static, but they evolve and adapt, just as the buildings they support. Pores can widen as soluble phases dissolve, hydrates recrystallize under new thermal regimes, microcracks form and heal through cycles of wetting and drying, while environmental pollutants add new layers of complexity, as sulfate ions generate gypsum veils or expand crystallization fronts within the pore network [9]. In this context, a successful conservation mortar must not only match the appearance or chemical composition of the original, but also its dynamic behavior. It must be strong enough to bind, yet weak enough to yield under stress, open enough to allow vapor passing, but dense enough to resist washout. This concept of "functional porosity" (the balance between cohesion and permeability) lies at the heart of compatibility [19]. When it is lost, even the best intentions can turn destructive: a too-dense repair mortar can trap moisture and salts, forcing decay into adjacent historic material.

In recent years, a new generation of materials has emerged to address these issues. Among the most promising are hydroxyapatite-modified lime mortars, in which calcium phosphate phases grow within the lime matrix, forming nanocrystalline bridges that increase cohesion and resistance to frost while maintaining the original breathability [20, 21]. This approach capitalizes on the advances that the modern materials science can provide, the resulting mortars being not only able to provide consolidation, but also an increased compatibility. Ultimately, the conservation of mortars and plasters is more about understanding the behavior of the ancient materials, and less about developing rigid solutions.

2.4. Interfaces and composite behavior

Every historic structure is, at its essence, a fine balance between different materials, and the most important area is at the interfaces between them. Within these thin, often invisible layers, chemistry and mechanics are mixed in ways that decide whether a building will endure or fracture. Weathering is very rarely a homogenous process, as time and environment do not act uniformly, but develop different layers with different characteristics. The outer layer of a stone façade or plaster wall may differ profoundly from the interior. At the exterior, pollutants condense, salts crystallize, and biological films form, giving rise to layers enriched in sulfates, oxalates, nitrates, or amorphous silica [22]. Under the exterior layer, is a transition zone (weaker, more porous, and chemically depleted) where internal cohesion begins to fade. The overlapping of these areas can create stress points that can affect the entire construction,

At these interfaces also lies the most difficult mission for the conservators. Although a consolidant or coating that reinforces the surface may offer a temporary illusion of stability, as the underlying layer continues to expand, contract, or absorb moisture, the stiffened exterior begins to delaminate [23]. Alternatively, a treatment that penetrates too deeply may disturb the hygroscopic balance of the stone, closing the pores through which vapor must pass, or altering salt migration routes. The goal is not depth for its own sake, but balance, an intervention that respects the physical and chemical characteristics of the material it seeks to protect. Considering all these factors, the modern analytical methods became indispensable tools of modern heritage science. Through cross-sectional mapping of porosity, ion concentration, and mineral phases, conservators can reconstruct the invisible architecture of decay. Techniques such as micro-CT imaging, Raman and FTIR mapping, or micro-XRF trace gradients from surface to core, offering a three-dimensional understanding of how deterioration advances and how treatments interact with these layers [24-26]. Every intervention must operate within a gradient of composition and stress, not against it.

3. Analytical methods and materials characterization

To understand the behavior and to evaluate the fate of the historical materials the first step is represented by the complete understanding of the nature and characteristics of the individual materials. Analytical methods provide the instruments for this evaluation, which allows the translation of "weathered stones" or "aged mortar", for example, into quantifiable phases or structures.

3.1. Classical analytical techniques

Among the analytical methods, X-ray diffraction (XRD) remains the most reliable and often used method to identify the crystalline phases. It can be used to evaluate the presence of the mineral phases connected to durability and decay (such as, i.e., calcite and dolomite in limestone, gypsum in sulfated crusts, portlandite in lime mortars) and to quantify their proportions [27]. This, in turn, allows the researchers involved to evaluate if the carbonation is complete or if gypsum accumulation threatens cohesion. Fourier-transform infrared spectroscopy (FTIR) is often used to detect what XRD cannot, such as the presence of amorphous hydrates, silanol groups, and organics. When coupled with thermal analysis (TG–DTG), it can be used to trace reaction kinetics (dehydration of hydrates, decarbonation of calcite, formation of sulfates), thus being useful in evaluating the rhythm of mineral change [28]. Raman spectroscopy, especially in its portable form, can provide important *on-site* information, regarding the presence of, for example, crystals of gypsum or calcium oxalate on a façade, allowing conservators to act with precision rather than presumption [29].

SEM–EDX provides information on both composition and morphology, showing how consolidation materials bind at the grain level. Micrographs have documented the formation of $CaCO_3$ bridges after nanolime and the nucleation of hydroxyapatite on marble, all microstructural signatures of macroscopic stability [5]. As previously mentioned, pore structure remains one of the most important characteristics of the historical stones. Mercury intrusion porosimetry (MIP) and gas adsorption quantify the geometry that plays a major role in moisture flow and salt crystallization, while ultrasonic velocity and drilling resistance tests translate these microstructural shifts into mechanical meaning [9]. Even polarized light microscopy, though older, still unveils the story of grain interlocking, microcracks, and recrystallization. Each technique, providing useful information by their own, can lead, when used together, to the obtaining of a wide array of information necessary for the selection of the appropriate treatment.

3.2. Emerging and non-invasive methods

As useful the classical analytical methods proved over the years, the necessities of the restorers for rapid, *on-site* information, able to support the process of decision making, led to the development of more advanced non-invasive technologies. Portable XRF, Raman, and FTIR devices have provided important advancements in field diagnostics, turning the sophisticated laboratory analyses, often time-consuming, into rapid analysis that can be performed directly on the artifacts, without any sampling. Mapping sulfur, chlorine, and iron across façades can be used to produce chemical “weathering maps” that guide conservation priorities.

An integrated, stepwise workflow, from in-situ survey through non-destructive and laboratory analyses to hygric–mechanical–chemical modeling supports evidence-based treatment design (Figure 1).

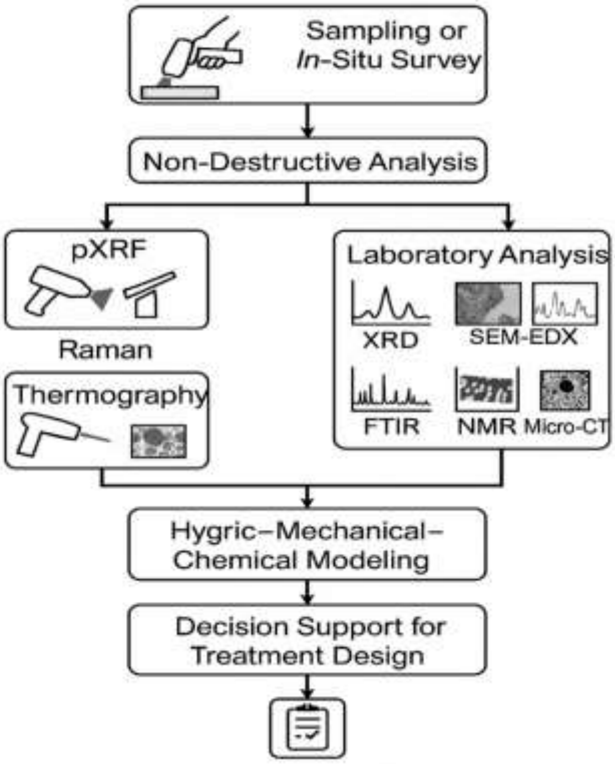

Fig. 1. Analytical workflow for heritage materials. Sampling or in-situ survey feeds non-destructive analyses (portable XRF - pXRF, Raman, thermography) and laboratory methods (XRD, SEM–EDX, FTIR, NMR, micro-CT). Results converge into hygric–mechanical–chemical modeling to provide decision support for treatment design

Solid-state nuclear magnetic resonance (NMR) provides insight into disordered or amorphous materials: the silicate networks in hydraulic mortars, the carbonate substitutions within hydroxyapatite films [26], while ToF-SIMS can be used to detect traces of organic residues or consolidant additives on treated surfaces (a chemical fingerprint of past interventions).

Micro-computed tomography (micro-CT) transformed the way internal structure is visualized. Three-dimensional reconstructions of pores and cracks now reveal how consolidants flow through the stone, which voids they fill, and where they stop [24]. Sequential scanning before and after treatment shows consolidation as a tangible volume change - the microscopic equivalent of healing. Thermography and fiber-optic reflectance spectroscopy (FORS) expand diagnostics into the macro-scale: infrared thermography exposes hidden moisture channels and delamination beneath plaster, while FORS tracks pigment fading on frescoes or façade paintings.

The next major challenge for this domain is data fusion and machine learning. By integrating spectra, images, and hygric data, chemometric models can discern subtle patterns invisible to the human analyst. Principal-component analysis (PCA) and clustering algorithms have been used to classify degradation states, predict problematic areas, and correlate chemical alteration with microstructural parameters [30].

3.3. Scale bridging and interpretation challenges

Despite the existence of modern and reliable instruments, one of the greatest challenges is represented by the translation of results: connecting data measured on the micro-scale to processes occurring across the structure. Laboratory measurements can describe cubic millimeters, while real walls suffer different processes over square meters. Bridging these scales demands not just numerical models and scientific rigor, but conceptual imagination. Experimental data can mislead if taken out of context. A porosity measured under vacuum may not reflect the same network under capillary tension; a phase identified as gypsum might in fact be a metastable hemihydrate at ambient humidity. Therefore, cross-validation (combining different techniques and interpreting results within environmental context) is essential.

Ethical limits also shape methodology: sampling must be kept to a minimum absolutely necessary, while invasiveness must be thoroughly justified [18]. This constraint has accelerated the development of portable multimodal instruments, capable of combining spectroscopic and imaging data in a single measurement. Europe-wide standardization efforts now aim to harmonize analytical workflows and metadata documentation. Journals and projects advocate for open repositories where spectra, micrographs, and data are archived with full metadata [31], which, over time, have the potential to transform heritage science into a cumulative discipline, in which future conservators can reanalyze the past data.

4. Conservation materials and strategies: designing with the material

If analysis is how we manage to identify the problem, the intervention is the response to these problems. A good conservation material is not the one that tries to change the nature of the substrate, but the one that works together with it. The best results are obtained when using mineral-compatible strategies, such as calcium-based consolidants for calcareous stones, silica networks for siliceous ones, and hybrid sequences calibrated to preserve vapor openness [5].

4.1. Nanolime

Nanolime's used now appears intuitive: to deliver $Ca(OH)_2$ nanoparticles into fine capillaries, and then let the stone finish the job - carbonation completes the bridge-building ($Ca(OH)_2 \rightarrow CaCO_3 + H_2O$). When this process is allowed to unfold under the right humidity and temperature, calcite micro-bridges form between grains, reestablishing the matrix, while leaving the pore network largely breathable, a balance that represents the signature of a successful nanolime treatment [32, 33].

Field studies in Mediterranean area have demonstrated that multiple thin applications (instead of a single saturation) yield more uniform strengthening and less chromatic shift. In calcarenite façades, this strategy produced durable cohesion gains with negligible whitening, resulting in encouraging reports [34]. Still, nanolime is not magic. Where dead-end pores dominate, carbonation can stall; where crusted surfaces restrict diffusion, penetration is minimal. And because carbonation is slow, post-treatment monitoring (ultrasound, drilling resistance, colorimetry, vapor diffusion) is essential to confirm that improvements are structural and not merely superficial [22].

4.2. Hydroxyapatite

If nanolime can be used to rebuild, hydroxyapatite (HAP) brings something new to the restoration area: mineral affinity without mineral identity. In well-tuned formulations, a phosphate solution reacts with calcium at the surface to precipitate HAP ($Ca_5(PO_4)_3OH$, or its carbonated variants) as an ultrathin, coherent layer. The importance of the treatment lies in the multiple characteristics of the HAP: apatites are chemically robust in mildly acidic conditions compared with calcite (which offers a buffer against urban atmospheres); in the same time, appropriately formed HAP films maintain vapor permeability while providing surface cohesion, especially valuable on polished marble or delicate carvings [5]. What was once a modern approach was translated in the last years into practice. The multi-year exposure of treated marble at the Royal Palace of Versailles is a rare and precious dataset: phosphate-treated surfaces retained their appearance, reduced deterioration rates, and kept water uptake within the natural range of untreated controls [35]. On the formulation side, ion-substituted and carbonated apatites (Mg, Sr, Zn; partial CO_3^{2-} incorporation) improve lattice compatibility and may influence adhesion and microstrain. Controlled studies show uniform coverage, low color change, and stable adhesion on calcareous substrates, all indicators of an appropriate consolidating film [5-7].

4.3. Silica and hybrid materials

Silica consolidants (such as ethyl silicate -TEOS precursors that hydrolyze and condense to SiO_2) are the treatment of choice for siliceous stones [36]. When the pore network is open and the application is controlled, silica gels can re-cement grains at depth and deliver strong mechanical gains. According to the literature data, the difference between success and failure is process control, as over-saturation or poor curing can create brittle surface crusts that crack and peel [37].

A modern approach is represented by the use of hybrid materials, combining, for example, silica depth with carbonate compatibility. In carefully sequenced programs (TEOS first to stabilize the skeleton, then nanolime to rebuild carbonate bridges), research groups reported reduced shrinkage, better flexural response, and crucially, preserved vapor diffusion when dosing and curing are optimized. On weathered sandstones with mixed cements, this hybrid approach has also proven a viable approach [37, 38].

4.4. Modern alternatives to repair mortars

Mortars represent one of the most important elements of a wall. They allow water vapor to pass, buffer salts, and fail before the stones do. The best repairs replicate the pore architecture and mechanical hierarchy of the original (slightly weaker, more permeable, and perfectly compatible) [39]. Among the modern materials proposed, one of the most interesting approaches is represented by hydroxyapatite-modified lime mortars. By dispersing HAP micro/nanophases into lime matrices, researchers have achieved higher cohesion and enhanced freeze–thaw resistance without sacrificing vapor openness or color neutrality. In cyclic tests and pilot sites, these formulations behave like smarter limes, contributing to the long-term preservation of the targeted materials [5, 40, 41].

5. Evaluation and monitoring: importance of evidence-based strategies

The best treatment is only as good as its evidence. Laboratory aging and field monitoring can transform the proposed solution from a promise into a performance. The aim is not to obtain a “perfect solution”, but to present the obtained results in a logical manner and data-supported conclusions [42].

5.1. Laboratory aging

Accelerated tests are a very important preliminary step for the real-world studies, imperfect, but indispensable. Salt cycling (Na_2SO_4, NaCl) probes crystallization damage, humidity/thermal cycles rehearse seasons, freeze–thaw tests stress capillaries to their limit [9, 43]. After each regime, the researchers must evaluate the results: capillary uptake should slightly decrease, vapor diffusion should remain open, strength should recover without surface embrittlement, and color shifts (ΔE) should stay below perceptible thresholds [44]. Phase-level checks by XRD/FTIR and microstructural checks by SEM or micro-CT confirm whether nanolime carbonated, TEOS formed continuous networks, or HAP crystallized as intended [24].

5.2. Field monitoring

In situ, non-invasive techniques provide indispensable support. Portable XRF, Raman, and FTIR allow repeated phase checks on the same patch of stone [25, 26], IR thermography can reveal hidden moisture paths, while embedded RH/temperature/strain sensors can evaluate the behavior of heritage sites through seasons. The Versailles study regarding phosphate-treated marbles is a model: measured at intervals over several years, the data showed stable appearance, controlled water uptake, and reduced decay, not just for a month or a season, but across multi-year exposure [35].

5.3. Desalination and ion transport

Poultices remain the first choice for extracting salts [42]. But when chloride fronts sit deep, or when surfaces are too fragile for repeated wetting, electrokinetic desalination provides a measured alternative. Low-voltage fields mobilize ions toward buffered poultices, carefully tuned electrolytes keep pH near neutral, and pulsed regimens limit side effects. Recent studies show substantial chloride/sulfate reduction at depth, with the masonry's carbonate fabric preserved [45, 46].

5.4. Metrics with meaning – when a treatment is a success

Depth of penetration, vapor diffusion, capillary sorption, ultrasound or drilling resistance, ΔE color stability, and re-treatability - these are not boxes to tick but important aspects to cover, which influences the future of a proposed solution [24, 44, 47]. Reporting them transparently enables comparisons across projects and climates and feeds the shared evidence base reviewers keep asking for. The maturity of our field will be measured by how comparable our results become.

6. Path ahead: current and future areas of research

As literature data suggests, three main guidelines can be expected to shape the future of this research area.

The first, and probably the most important one, is that chemical compatibility is more important than brute force. Treatments are most probable to succeed when they are fully compatible with the substrate (calcite from nanolime, apatite from phosphate, silica from TEOS), while hygric openness is a non-negotiable design constraint. The literature data supports a very clear principle: compatibility first, performance second [5, 34].

The second principle, is that standardization should not be seen as bureaucracy but as memory. Without harmonized hygric tests, color and mechanical thresholds, our field can't remember what works. The push for metadata-rich, open repositories and comparable protocols is not academic housekeeping; it is the engine of cumulative knowledge [31]. Publication of raw spectra, micrographs, and data sets should be encouraged.

Finally, sustainability represents the new durability. Eco-compatible mortars, water/alcohol-based systems, low-toxicity formulations, and climate-stress testing are not add-ons; they are the context in which all heritage will now live. Phosphatemodified limes are a small but meaningful example: more resilient, still sacrificial, and anchored in benign chemistry [43].

The conservation science is slowly moving towards predictive conservation [30]. With time-series monitoring, machine learning, and mechanistic models, we can move from reacting to anticipating.

Conclusions

If there is a single lesson from the last two decades, it is that we must always consider the "memory" of the materials. Stones and mortars carry within their pores and phases a record of the climates they have endured and the interventions we have tried. Researcher's role is to read that record, respect its logic, and intervene with care.

Nanolime shows how a material can be persuaded to heal as itself, hydroxyapatite reveals how a related mineral can prove useful, while TEOS and its hybrids show how modern composites can be used. The future of this area is clear: standards that travel, datasets that endure, and materials that are fully compatible with the historical ones. If we can keep our chemistry consonant and our data comparable, we will have done more than conserve buildings; we will have crafted a scientific language of care - one that future generations can read, replicate, and refine.

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