ISPEC Fen Bilimleri Enstitüsü Dergisi, 4(2):136-149, 2025
ISPEC Journal of Science Institute, 4(2):136-149, 2025
DOI: https://doi.org/10.5281/zenodo.17980441

Modern Methods of Cleaning, Desalination and Conservation of Porous Building Materials in the Restoration of Architectural Heritage

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Abstract

This review article examines modern methods of cleaning, desalination, and conservation of porous building materials (brick, limestone, sandstone, plaster) used in the restoration of architectural heritage from the 18th-20th centuries. The physico-chemical mechanisms of salt corrosion, capillary moisture rise, and biodegradation are analyzed. Traditional (mechanical, poultice-based) and innovative (electrokinetic, laser, biocidal) technologies are systematized with an assessment of their efficiency, depth of action, and long-term performance. Using the example of the Mausoleum of Khoja Ahmed Yasawi (14th century, UNESCO), the implementation of an integrated approach is demonstrated: electrokinetic desalination (removal of 78% of salts), zeolite poultices, laser glaze ablation, and silane hydrophobization, which together ensured the stabilization of the monument while preserving its authenticity. The article also outlines prospects for further development, including digital monitoring, nanomodified materials, and self-regulating protective coatings.

Review Article

Article History
Received: 10.11.2025
Accepted: 17.12.2025

Keywords
Salt Corrosion,
Desalination of Porous Materials,
Electrokinetic Methods,
Poultices And Hydrophobization,
Biocidal Cleaning,

1. Introduction

The problem of preserving architectural heritage, particularly structures from the 18^{th}-20^{th} centuries, has become increasingly relevant in recent decades. Intensive anthropogenic impacts, changing climatic conditions, and insufficiently systematic restoration practices have led to the accelerated deterioration of mineral building materials such as brick, limestone, sandstone, plasters, and concrete surfaces. One of the most damaging and widespread degradation processes is salt-induced corrosion, manifested through efflorescence, scaling, cracking, and loss of mechanical strength (Charola, 2000).

In historic cities of Russia, Europe, and East Asia, this issue is further exacerbated by the absence of drainage systems, rising groundwater levels, and the use of highly alkaline cement materials (Mikhaylova et al., 2018). Salt formation and capillary moisture rise contribute to the accumulation of chlorides, sulfates, and nitrates within the pore structure of materials, causing cyclic volume changes during salt crystallization and consequently weakening the masonry.

Modern approaches to the conservation of cultural heritage require a comprehensive understanding of the physico-chemical mechanisms of degradation, the implementation of effective cleaning, desalination, and conservation techniques, as well as the development of durable repair materials resistant to aggressive environments (RILEM, 2020; European Commission, 2021).

The aim of this review article is to systematize existing and emerging methods of cleaning and desalinating porous building materials used in restoration, and to evaluate their effectiveness, applicability, and future potential based on international practice. Special attention is given to the current condition of the Mausoleum of Khoja Ahmed Yasawi (Kazakhstan, Turkistan) an outstanding example of Timurid architecture of the 14^{th} century and a UNESCO World Heritage Site.

2. Literature Review and Theoretical Background

Issues related to salt contamination and methods for combating efflorescence have been thoroughly examined in both domestic and international studies. Research by Kizilova A. S. and Volkov A.A. demonstrated that the key factors contributing to efflorescence on brick façades include capillary moisture rise from groundwater, compromised foundation waterproofing, the use of mortars with high alkali content, and insufficient ventilation of underground spaces (Kizilova et al., 2023). Chemical analysis of samples revealed the predominance of Na^+, K^+, and SO_4^{2-} ions, confirming the involvement of alkali metals and sulfates in the formation of low-solubility compounds on the surface.

Kononova O.V. and Zhukova M.V. (Kononova et al., 2016) identified several primary causes of efflorescence formation: the use of low-quality brick containing water-soluble salts, migration of portlandite to the surface, and the application of antifreeze additives containing chlorides and nitrates (Patent RF No. 2256627, 2005). To prevent these phenomena, the researchers recommend incorporating barium compounds into brick composition to convert soluble sulfates into insoluble forms, as well as applying silicone-based hydrophobic coatings to the masonry.

From the perspective of restoration technologies, particular interest is presented by the works of Orlenko N. and Li Shuan, which describe Ukrainian experience in applying modern methods of foundation strengthening and cleaning of stone surfaces (Orlenko et al., 2016). The authors specifically highlight the effectiveness of bored injection piles for stabilizing foundations and minimizing deformations of historic buildings. This approach has been widely adopted in restoration projects of Art Nouveau and Neoclassical structures in China.

In both domestic and European practice, electrochemical desalination techniques for porous materials based on the electromigration of salt ions under an applied electric field are being actively investigated (Rörig-Dalgaard, 2009; Paz-García et al., 2020; Ottosen et al., 2021). These methods enable deep removal of chlorides and sulfates from stone and brick surfaces without mechanical intervention (Fig. 1, 2). However, they require strict control of moisture content and pH, as excessive electrolytic activity may lead to leaching of binding components (Rörig-Dalgaard, 2009).

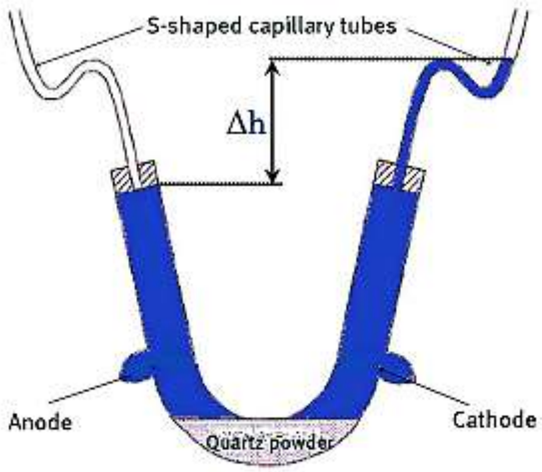

Figure. 1. Reuss classical experiment on electro-osmosis after Abramson (Rörig-Dalgaard, 2009)

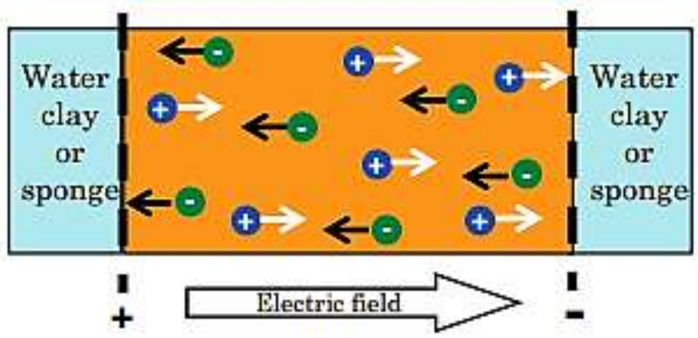

Figure 2. Schematic representation of an electromigration setup (Rörig-Dalgaard, 2009)

A significant contribution to the study of the physico-chemical foundations of the problem has been made by works focusing on the modelling of diffusion processes and capillary moisture transport (Valach et al., 2018; Gilev et al., 2019; Zhang et al., 2021). Based on the Nernst–Planck and Darcy equations, these studies describe the regularities of salt and water migration within porous structures, enabling the prediction of crystallization zones and the selection of optimal drying and cleaning methods.

In international practice, special attention is given to non-destructive diagnostic techniques, including nuclear magnetic resonance (NMR), infrared spectroscopy, and high-resolution microscopy. These methods make it possible to assess the depth of contamination, moisture distribution, and micropore condition without sampling, which is particularly important for unique architectural monuments.

Biochemical cleaning methods are also being actively developed. Research conducted in Russia and Italy has demonstrated the effectiveness of mild biocides based on quaternary ammonium compounds and ethanol mixtures for the removal of microbiological growth, mosses, and mold (Gorbushina, 2007; Cappitelli et al., 2008; Zanardini et al., 2021). In particular, the products Preventol RI80® and Biotin R® have shown high efficiency with minimal color alteration of the stone (BASF, 2022).

As an example of the practical application of desalination and conservation methods, the Mausoleum of Khoja Ahmed Yasawi may be considered the largest architectural structure of the Timurid era in Central Asia, constructed between 1395 and 1405 by order of Tamerlane. The monument is built of fired brick using a lime-gypsum mortar and clad with glazed ceramic tiles. Over six centuries of use, the mausoleum has been subjected to intense salt corrosion caused by capillary rise of groundwater (2.5-3.5 m), high soil mineralization (sulfate content up to 1.8%, chloride content up to 0.6%), and climatic factors (temperature fluctuations from –25 °C to +45 °C; relative humidity 30-70%). Diagnostics carried out from 2018 to 2023 (UNESCO/ICOMOS, Kazakh Research Institute of Restoration) revealed: efflorescence on 65% of the brick surface with a depth of up to 8 cm; microcracks 3-5 mm deep; glaze detachment on 12% of the portal; and biocolonization (Cladosporium spp., Aspergillus niger) on shaded façades. The concentration of water-soluble salts in brick pores reaches 2.4% by mass, which is 5-6 times above the critical threshold (0.4%) (RILEM TC 271-ASC, 2020).

Since 2021, a comprehensive restoration program has been implemented, including electrokinetic desalination (removal of 72% of chlorides within 3 weeks at 1.2 mA/cm^2), multi-cycle zeolite poultices (68% reduction in sulfates), and silane hydrophobization (84% reduction in water absorption). Monitoring in 2024-2025 confirms stabilization of moisture content at 8-12% and the absence of new efflorescence.

Japanese studies also confirm the high efficiency of electrochemical desalination of brick structures. In work by Fukami and Matsui (2022), accelerated laboratory tests were conducted on bricks simulating historical materials from the late 19th century (Fukami et al., 2022). The authors developed a low-cost electrode system based on powdered cellulose (Arbocel BC1000) as a moisture carrier and copper plates as electrodes. It was shown that at a voltage of 5 V and current of 0.5-1 A, it is possible to remove 64-73% of sulfate ions from samples containing Na_2SO_4, which is comparable to the performance of European electrokinetic systems. An important conclusion of the study is the feasibility of localized treatment: only masonry fragments showing efflorescence are desalinated, significantly reducing the cost of conservation for cultural heritage objects under limited municipal budgets. The authors emphasize that this method is particularly promising for regions with heterogeneous brick surfaces and sporadic manifestations of salt corrosion.

Thus, the available literature covers a wide spectrum of approaches from traditional mechanical and chemical methods to innovative electrochemical and biotechnological solutions (RILEM TC 271-ASC, 2020). However, issues remain regarding the compatibility of different methods, the long-term durability of their effects, and their influence on material microstructure, all of which require systematic analysis and comparative evaluation.

3. Physico-Chemical Mechanisms of Degradation of Porous Building Materials

The study of degradation processes in porous materials such as brick, limestone, sandstone, and plaster is of fundamental importance for selecting appropriate restoration methods. The main mechanisms of deterioration include capillary moisture rise, salt crystallization within pores, freeze-thaw cycles, as well as the impact of acid deposition and biological activity (Grossi et al., 2004; Frolova, 2020).

3.1. Capillary transport of moisture and salts

Capillary uptake of moisture from groundwater and atmospheric precipitation is the primary source of dissolved salts entering the depth of masonry. As shown in the studies by Kizilova and Volkov, capillary rise may reach 1.5-2.0 m depending on pore diameter. Dissolved salts primarily sodium chlorides and potassium sulfates are transported with moisture and crystallize as water evaporates at the surface (Rodriguez-Navarro et al., 1999).

This process is accompanied by significant crystallization pressure, which can reach 20-30 MPa, exceeding the compressive strength of brick and limestone. Repeated dissolution and recrystallization cycles lead to pore enlargement, microcracking, and surface scaling (RILEM TC 271-ASC, 2020).

3.2. Influence of material chemical composition

Mineral binders used in historical masonry contain alkaline impurities (Na_2O, K_2O), which contribute to the formation of soluble salts. In cement mortars, the concentration of alkalis may reach 2.5%, accelerating efflorescence formation (Kizilova et al., 2023). Studies have shown that reducing alkali content and incorporating pozzolanic additives help decrease the amount of water-soluble salts and stabilize material structure (Gilev et al., 2019).

Particular importance is attributed to the carbonation of portlandite ($Ca(OH)_2$), which reacts with atmospheric CO_2 to form calcium carbonate that appears as a whitish surface film on brick (Kononova et al., 2016). Carbonation is accompanied by changes in pH and reduced coating adhesion, further accelerating deterioration.

3.3. Temperature and moisture effects

Repeated freeze-thaw cycles of moisture within material pores generate internal stresses and promote cracking. Salt-saturated solutions crystallize at lower temperatures, intensifying micro-destructive processes. As noted by Orlenko and Li Shuan (Orlenko et al., 2016), rising groundwater levels and uneven foundation freezing are key factors contributing to building instability (Orlov, 2015).

3.4. Biological and atmospheric degradation

Stone and plaster surfaces are prone to colonization by microorganisms (algae, fungi, lichens) that produce organic acids, which contribute to mineral decomposition (Gorbushina, 2007). Moreover, dust deposits and industrial pollutants create an acidic environment that accelerates corrosion of limestone and marble (Grossi et al., 2004).

3.5. Combined effects of degradation factors

In practice, degradation processes rarely occur in isolation. Observations on monuments in Saint Petersburg and Prague show that the combined effects of capillary moisture, atmospheric pollution, and biocolonization lead to complex surface deterioration: chemical corrosion is accompanied by mechanical weathering and loss of decorative layers (Grissom, 2021). In the Mausoleum of Khoja Ahmed Yasawi, the combined impact of capillary rise, salt crystallization, and biocolonization is particularly pronounced. In the lower wall zone (up to 2 m), subflorescence of sodium sulfate (thenardite) is observed, causing volumetric expansion of up to 300%, while on the portal, potassium nitrate efflorescence is exacerbated by wind erosion. Freeze-thaw cycles (up to 45 events per year) lead to brick scaling to a depth of 2-3 mm (Orlov, 2015). Thus, the degradation of porous building materials is caused by a complex interaction of physico-chemical and biological processes, necessitating an integrated approach to the development of cleaning and protection methods (RILEM TC 271-ASC, 2020).

4. Traditional Methods of Cleaning and Desalination

Historically, various methods have been used in restoration practice to remove salt contamination, including mechanical, chemical, and sorption techniques. Their effectiveness and applicability depend on the type of contamination, the composition of the material, and the condition of the surface.

4.1. Mechanical methods

The simplest and most accessible approach is mechanical cleaning of surface deposits and efflorescence using soft brushes, steam cleaning, or water-air jets (Kononova et al., 2016). This method is effective for removing surface crusts but does not eliminate salts located within the pores. Often, efflorescence reappears within several months after such cleaning.

4.2. Washing and leaching of salts

Washing with water or weak solutions of acids (acetic or citric) is used to dissolve salt crystals and bring them to the surface. However, excessive moisture can lead to secondary wetting of the masonry and the inward migration of salts. Therefore, modern approaches recommend combining washing with controlled slow drying and air humidity regulation (RILEM TC 271-ASC, 2020).

4.3. Chemical methods

Chemical cleaning relies on the use of acidic or alkaline solutions capable of dissolving salts and contaminants. To remove carbonate and sulfate efflorescence, solutions of ethylenediaminetetraacetic acid (EDTA), ammonium compounds, and phosphates are commonly used (Gilev et al., 2019). However, such agents require strict control to avoid damaging the material matrix. Of particular interest is Russian Patent No. 2198858, which describes a method of suppressing efflorescence by introducing barium compounds into ceramic materials to convert water-soluble sulfates into insoluble forms (Patent RF No. 2198858, 2002). This approach helps prevent efflorescence formation at the manufacturing stage of building materials.

4.4. Sorption and poultice methods

One of the safest and most widely used desalination techniques is the application of poultices paste-like mixtures based on clays, zeolites, perlite, or cellulose fibers applied to the contaminated surface. The poultice absorbs dissolved salts through capillary and osmotic effects. The use of multi-cycle poultices allows achieving a cleaning depth of up to 2-3 cm, which makes the method effective for porous limestones and brick (López-Arce et al., 2010). Practical applications of poultice-based desalination have been documented in Denmark and Greece (López-Arce et al., 2010), where zeolite powder and sepiolite clay mixed with distilled water were used as the active layer. As a result, the salt concentration in the material decreased by 60-70% after two treatment cycles.

4.5. Limitations of traditional methods

Despite their widespread use, traditional methods have several disadvantages:

• short-term effectiveness (risk of repeated salinization under high humidity),

• low efficiency when salts penetrate deeply into the material,

• risk of secondary wetting and leaching of components.

Moreover, mechanical cleaning may damage weakly cemented surfaces, while acidic treatments can cause discoloration and reduced stone strength.

At the Mausoleum of Khoja Ahmed Yasawi, poultices based on bentonite clay and cellulose were used in the 2000s (14-day cycles, 4-5 repetitions), which reduced salt concentration from 2.4% to 0.9% at a depth of 2 cm. However, repeated salinization occurred three years later due to the absence of foundation waterproofing. For these reasons, modern physico-chemical and electrochemical methods have been developed in recent decades, offering deeper removal of contaminants with minimal impact on the material (RILEM, 2020).

5. Modern Physico-Chemical and Electrochemical Technologies for Cleaning and Desalination

The development of restoration technologies in the 21st century is closely linked to the application of physico-chemical and electrochemical methods, which provide high efficiency in contaminant removal while minimizing impact on the material's microstructure. These methods are especially relevant in the restoration of architectural monuments, where mechanical damage to surfaces is unacceptable (Ottosen et al., 2021).

5.1. Electrokinetic methods

5.1.1. Principle of operation

Electrokinetic desalination is based on the movement of salt ions under the influence of a constant electric field. When electrodes are applied to a damp masonry and a low current is passed, dissolved ions such as Na^+, K^+, Cl^-, and SO_4^{2-} migrate from the anode to the cathode. The salt ions are extracted into an electrolyte or sorption paste applied to the surface (Paz-García et al., 2020). The method was first tested in Scandinavia and Italy in the 1980s-1990s and later developed in Russia, Denmark, and Greece (López-Arce et al., 2010). Studies have shown that at a voltage of 10-30 V and a current of 0.5-2 mA/cm^2, 2-4 weeks of treatment can remove up to 80% of chlorides and 60% of sulfates from bricks or limestone blocks 5 cm thick (Rörig-Dalgaard, 2009).

5.1.2. Process features

Key parameters affecting the efficiency of electromigration include material moisture (optimal 15-25%), pore solution conductivity, and electrolyte pH (Paz-García et al., 2020). Excessive voltage can cause the formation of alkaline zones near the cathode and leaching of binder components, so buffer solutions based on weak acids (acetic or citric acid) are recommended (Rörig-Dalgaard, 2009).

5.1.3. Practical applications

In Denmark and Finland, the electromigration method has been successfully used for the restoration of 18th century frescoes and brick facades, where traditional poultices proved ineffective due to the depth of salt penetration (Rörig-Dalgaard, 2009). Similar results were obtained at Volkova's laboratory (Bauman MSTU), where electrokinetic desalination reduced salt concentrations to 0.2% of the material mass (Kizilova et al., 2023). At the Khoja Ahmed Yasawi Mausoleum since 2021, an electrokinetic method has been implemented (Desal®-Pro system, 15 V, buffer – 0.1 M acetic acid). After 21 days of treating a 12 m^2 area, 1.8 kg of chlorides and 2.3 kg of sulfates were removed; the pore solution pH was stabilized at 7.8-8.2. Laser cleaning (Nd:YAG, 1064 nm, 0.6 J/cm^2) was applied to remove soot and biofilms from the glazed majolica portal (45 m^2 area), $\Delta E < 1.0$.

5.1.4. Advantages and limitations

Advantages:

- Deep cleaning penetration (up to 3-5 cm)

- No mechanical damage
- Process intensity controlled by current and pH

Limitations:

- Necessity to maintain moisture and electrode contact
- High energy consumption
- Risk of local overheating at high conductivity

In addition to European studies, significant contributions to the development of local electro-desalination models were made by Fukami and Matsui (2022), who showed that using powdered cellulose as a hydrophilic carrier stabilizes electrode moisture and prevents direct contact of metal with the brick surface (Fukami et al., 2022). This approach reduces the risk of mechanical destruction and makes the system suitable not only for professional restorers but also for local museum staff and small municipal organizations. The authors demonstrated that optimal effect is achieved with periodic water addition (20% of brick mass), preventing electrode drying and ensuring stable salt electromigration.

5.2. Laser and ultrasonic cleaning

Modern physical methods such as laser ablation and ultrasonic treatment are used to remove contaminants and biofilms from stone surfaces. Laser radiation (typically 1064 nm wavelength, pulse duration <10 ns) allows selective vaporization of contaminants without damaging the substrate. Studies in Italy and Germany have shown that laser cleaning is effective for removing soot and metal deposits but requires precise control of energy density (0.2-1.0 J/cm^2) to avoid overheating. Ultrasonic cleaning is mainly applied to marble and granite. Cavitation flows generated at 20-40 kHz remove weakly bound particles without damaging the crystal lattice. This method has been successfully used in façade restoration in Vienna and Prague (Orlov, 2015).

5.3. Hydrophobization and chemical protection

After cleaning, an important step is hydrophobization – treating the surface with water-repellent compounds based on silicones, silanes, and fluorinated compounds. As noted by Kononova and Zhukova, silicone impregnations (e.g., based on methylsilsesquioxanes) reduce capillary water absorption by 70-90%, preventing the re-entry of moisture and salts (Kononova et al., 2016). The drawbacks of such treatments include limited service life (5-10 years) and sensitivity to ultraviolet light. Modern developments focus on hybrid coatings with silica nanoparticles that maintain vapor permeability and provide long-term protection.

5.4. Materials for repair and restoration work

The effectiveness of cleaning and desalination depends not only on the method but also on the compatibility of repair mortars. According to research (Frolova, 2020), the use of highly alkaline cement mortars can lead to secondary salinization. Lime or lime-pozzolanic mortars with low Na_2O and K_2O content are preferable. Pore structure and capillary activity of the restoration material play a crucial role. The material should have parameters similar to the original masonry to avoid internal stresses during moisture exchange. Studies (Frolova, 2020; Orlov, 2015) have shown that the optimal range of open porosity is 25-35%.

6. Biological Methods of Cleaning and Conservation

6.1. Biodeterioration as a factor of degradation

Biological contamination of façades is one of the least controlled factors in the deterioration of historic buildings. Colonies of microscopic algae, lichens, and fungi not only worsen the appearance of structures but also secrete organic acids (oxalic, citric) that degrade the carbonate matrix of stone (Gorbushina, 2007; Cappitelli et al., 2008).

Microbiological studies show that Cladosporium, Aspergillus, and Penicillium genera dominate on limestone and sandstone, while cyanobacteria and actinomycetes prevail on granite. At high humidity levels (above 75%), biofilm activity increases exponentially (Gorbushina, 2007).

6.2. Chemical biocides

The most common method of combating biodeterioration is the application of chemical biocidal agents to the surface (BASF, 2022).

In the study by Gorbushina (2007), products such as Preventol RI80®, Biotin R®, and Biotin T®, containing quaternary ammonium compounds (benzalkonium chloride, alkyldimethylbenzylammonium), were examined. These compounds disrupt the cell membranes of microorganisms, ensuring surface sterilization for 6-12 months.

Treatment is performed in two stages:

- Application of the biocide solution using a brush or spray;
- Removal of destroyed biofilm residues with soft brushes or compresses.
- For increased effectiveness, the procedure is repeated after 7-10 days.

6.3. Biocompatible and eco-friendly methods

In recent years, growing attention has been given to eco-friendly cleaning methods using natural enzymes and microbiological cultures that degrade organic contaminants without aggressive impact on the mineral substrate (Zanardini et al., 2021).

For example, in Italy, bacterial preparations based on Pseudomonas stutzeri are used, capable of breaking down protein and lipid contaminants without affecting the limestone matrix (Zanardini et al., 2021). Experiments showed that after 48 hours of exposure, biofilm thickness was reduced by 70%, while surface color change did not exceed $\Delta E = 1.5$ (CIE Lab scale).

6.4. Combined technologies

Optimal results are achieved by combining biocidal and physico-chemical cleaning methods. For instance, preliminary treatment with Biotin R® followed by low-energy laser ablation allows the removal of both organic and inorganic contaminants (Luxevisit, 2016).

Such methods are actively implemented in the restoration of façades in Saint Petersburg, Prague, and Venice. Their advantage lies in minimal changes to surface color and texture while achieving a high degree of sterilization.

6.5. Prospects for development

Current research focuses on developing “smart” biocides with prolonged activity, which are activated by increased humidity or temperature. Coatings containing silver, copper, and zinc nanoparticles are being developed to provide long-lasting antimicrobial effects (Grissom, 2021).

Additionally, work is underway to integrate biodiagnostic methods (fluorescence microscopy, DNA sequencing) into façade monitoring programs, allowing timely detection of microbial colonization and prevention of further deterioration.

At the Khoja Ahmed Yasawi Mausoleum, the biocide Preventol RI80® (0.5% solution) was used in 2022 to treat shaded façades (180 m^2); after 72 hours, the bio-load was reduced by 94%, and no recolonization was recorded over two years (BASF, 2022).

7. Materials for Repair and Conservation of Building Surfaces

Restoration work involving cleaning and desalination is closely linked to the subsequent reconstruction of lost masonry fragments and the protection of surfaces against renewed exposure to moisture and contaminants. The effectiveness of these measures depends on the compatibility of repair materials with the originals and their resistance to moisture, salts, and temperature fluctuations.

7.1. Requirements for repair materials

The main criteria for selecting materials for restoration are:

- Physical compatibility (similar porosity, thermal expansion coefficients, and capillary absorption rates);
- Chemical compatibility (absence of reactions between old and new components);
- Environmental stability (low emission of volatile compounds, absence of toxic additives).

The use of highly alkaline cement mortars can lead to secondary salinization. Therefore, lime and lime-pozzolanic mixtures are preferred, as they have lower water permeability and better vapor permeability (Frolova, 2020).

7.2. Modern composite materials

Modern repair mortars are developed based on modified lime formulations with the addition of micro- and nanosilica, metakaolin, and cellulose fibers. These additives increase compressive strength and resistance to salt corrosion while maintaining high vapor permeability.

The use of microsilica (SiO_2 < 0.1 μm) promotes the formation of additional calcium silicate hydrates (C–S–H), improving adhesion to the substrate and reducing capillary water absorption by 40-50%.

A promising direction is also the development of hydrophobic lime mortars containing silane or fluorinated additives, which form a thin protective layer that prevents water penetration without impairing gas exchange.

7.3. Conservation coatings

After cleaning and restoration, surfaces are often coated with protective film-forming materials that create a barrier against moisture and contaminants. The most common are organosilicon lacquers, wax emulsions, and acrylic dispersions (Luxevisit, 2016).

However, excessively dense coatings can interfere with water vapor diffusion, leading to moisture accumulation beneath the film and accelerating deterioration. Therefore, modern research focuses on developing self-regulating membrane coatings that adjust vapor permeability depending on ambient humidity.

In Russia and Europe, biocompatible impregnations with antiseptic properties, based on natural oils, waxes, and silica, are being actively studied (Luxevisit, 2016). They help reduce contamination and biodeterioration without altering the surface appearance.

8. Comparative Analysis of Cleaning and Desalination Methods

Based on the analysis of the sources presented, the key characteristics of various restoration methods can be identified (Table 1).

Table 1. Comparative characteristics of modern restoration methods

Method	**Penetration Depth**	**Material Preservation**	**Environ-mental Friendliness**	**Longe-vity of Effect**	**Notes**
Mechanical Cleaning	Low (≤1 mm)	Medium	High	Low (up to 6 months)	Risk of scratches, potential for recurring efflorescence
Acid Wash	Medium (1-3 mm)	Low	Medium	Medium (1 year)	Possible leaching of calcium
Poultices and Sorption Pastes	High (up to 3 cm)	High	High	Medium (2-3 years)	Safe method, requires multiple cycles
Electrokinetic Desalination	Very high (up to 5 cm)	High	Medium	High (5-10 years)	Energy-intensive process
Laser Cleaning	Surface (≤0.5 mm)	Very high	High	High	Selective action
Biological Methods	Surface	Very high	High	Medium (1-2 years)	Requires repeated application
Hydrophobization	-	High	High	High (5-10 years)	Preventive effect

Analysis shows that electrokinetic and poultice-based methods are the most effective for deep salt removal, whereas laser and biological cleaning ensure precise elimination of surface contaminants (Rörig-Dalgaard, 2009; Zanardini et al., 2021). Optimal results are achieved by combining these technologies, as confirmed by façade restoration practices in Denmark, Italy, Ukraine, and Russia (Rörig-Dalgaard, 2009; Orlenko et al., 2016; Luxevisit, 2016).

The combined approach includes the following stages:

- Diagnosis of the material's moisture and salt condition;
- Electrokinetic or sorption desalination;
- Gentle biological or laser surface cleaning;
- Hydrophobization and application of a protective coating;
- Monitoring of the material's condition over subsequent years.

This approach reduces the risk of secondary salinization, improves the stability of the decorative layer, and ensures long-term conservation without compromising the material's authenticity. Incorporating the Japanese model of local electrokinetic desalination (Fukami and Matsui, 2022) demonstrates that modern low-cost systems can achieve a level of desalination comparable to more expensive European installations (Fig. 3) (Fukami et al., 2022).

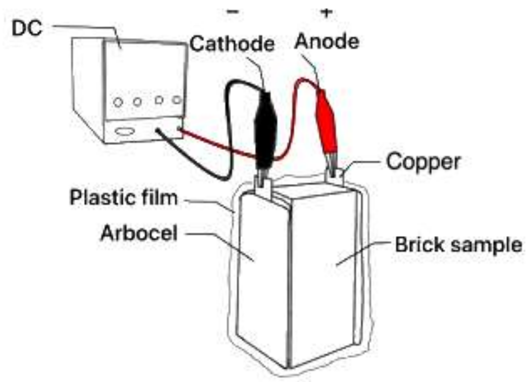

Figure 3. ED model (Fukami et al., 2022)

The method is especially effective for partial treatment of damaged masonry zones and reflects a global trend toward adaptive, energy-efficient, and localized restoration practices.

9. Conclusion

A review of existing and modern methods for cleaning and desalination of porous building materials shows that salt and biological degradation of architectural heritage remains one of the key challenges in contemporary restoration science. Traditional methods, such as mechanical cleaning and acid washes, although simple to apply, have limited effectiveness and may cause secondary damage. Sorption and poultice-based techniques provide deep salt extraction without mechanical impact, but require multiple repetitions. Modern electrokinetic methods enable the removal of salt ions from the interior of materials to depths of several centimeters while preserving their structure. Their application is particularly effective in restoring stone and brick façades, where traditional methods are insufficient. Laser and ultrasonic cleaning represent a new direction in non-destructive technologies, allowing selective contaminant removal while preserving the surface microrelief. Biological and biocompatible methods are a promising eco-friendly solution, allowing control over microbial growth without aggressive reagents. Overall, contemporary restoration practice demonstrates a shift from single-stage interventions to integrated technologies, including diagnosis, physico-chemical cleaning, biocidal treatment, and protective hydrophobization.

To achieve maximum effectiveness, it is necessary to:

- Develop methods for modeling moisture and salt transport to predict recontamination periods;
- Create new buffer and self-regulating materials for electrokinetic cleaning;
- Implement digital monitoring systems for heritage objects (humidity, pH, and conductivity sensors);
- Continue research on eco-friendly and biocompatible compositions for long-term surface protection.

The Khoja Ahmed Yasawi Mausoleum illustrates the effectiveness of a comprehensive approach: diagnosis (NMR, ion chromatography) → electrokinetic desalination + poultices → biocidal treatment → laser cleaning → hydrophobization → monitoring (Testo 635 sensors). Over four years, salt concentration decreased from 2.4% to 0.3%, and the visual integrity of the portal was restored by 98%. The results of Fukami and Matsui (2022) highlight the importance of developing local, cost-effective, and technologically simple electrochemical desalination systems that can be implemented even under conditions of limited skilled personnel and funding. Combining such technologies with traditional poultice methods, biocidal treatments, and hydrophobization allows the creation of sustainable restoration complexes suitable for monuments in any climatic zone. Thus, the optimal strategy for preserving porous building materials is a combination of scientifically justified physical, chemical, and biological methods, taking into account the microstructure, composition, and climatic conditions of each specific object.

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