

## Review

# A Review of Research Progress on the Deterioration Mechanisms and Conservation Treatments of Earthen Heritage Sites in China

Zhihao Wan <sup>1</sup>, Jingjing Shao <sup>1,2,\*</sup>, Lijuan Wang <sup>1</sup> and Bo Li <sup>3</sup>

<sup>1</sup> School of Civil and Transportation Engineering, Ningbo University of Technology, Ningbo 315211, China; 15070051811@139.com (Z.W.); wanglijuan@nbut.edu.cn (L.W.)

<sup>2</sup> Xiangshan Research Institute, Ningbo University of Technology, Ningbo 315211, China

<sup>3</sup> Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo 315100, China; bo.li@nottingham.edu.cn

\* Correspondence: jingjing.shao@nbut.edu.cn

## Abstract

As tangible witnesses and cultural carriers of the evolution of Chinese civilization, earthen heritage sites embody outstanding historical, cultural, and scientific value. However, due to the heterogeneity among sites and their long-term exposure to complex environmental and anthropogenic pressures, their conservation faces numerous challenges. This paper provides a comprehensive review of the deterioration mechanisms of earthen heritage sites in China induced by environmental and anthropogenic factors, with particular emphasis on the effects of individual factors, such as salt-induced erosion, wetting–drying cycles, wind erosion, microbial activity, freeze–thaw cycles, and human activities, as well as the coupled actions of multiple factors. It further summarizes recent progress in protective technologies developed in response to these mechanisms, as well as integrated conservation strategies for coping with coupled deterioration effects. In recent years, the intrinsic linkage mechanisms between external environmental conditions and the engineering performance of earthen heritage sites have become a research focus. This review aims to deepen the understanding of environmental degradation processes in earthen heritage sites and to provide theoretical and technical support for the scientific formulation of targeted preventive conservation, repair, and strengthening measures.

**Keywords:** earthen heritage sites; deterioration mechanisms; protective technologies; environmental factors; coupled effects

## 1. Introduction

Earthen heritage sites refer to ancient architectural remains constructed primarily with earth as the building material, such as ancient cities, tombs, and dwellings [1]. In this review, the term “earthen heritage sites” is used as an umbrella concept covering earth-based architectural remains constructed using different techniques, including rammed earth, adobe or earthen-block masonry, cob, earthen renders or plasters, wattle and daub, and related mixed earthen systems. To avoid terminological ambiguity, “earth”, “earthen material”, and “earthen fabric” are used to refer to built earthen components of heritage structures, whereas “soil” is retained where the discussion concerns ground conditions, geotechnical soil, or laboratory-tested site-soil specimens. However, because the currently available deterioration and conservation studies are largely concentrated on rammed-earth walls and exposed earthen-wall remains, the applicability of the reviewed mechanisms and conservation measures to other earthen construction forms should be considered



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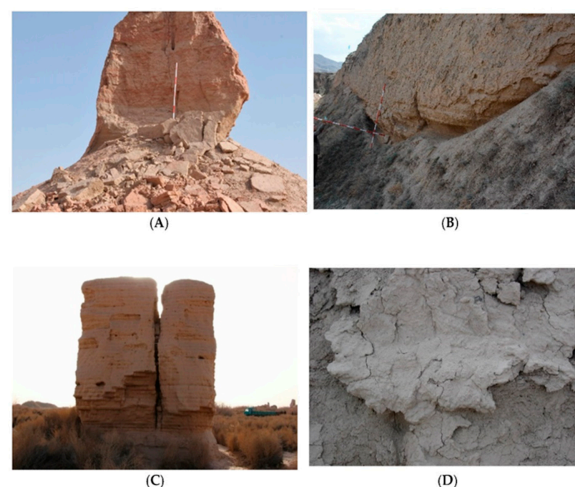
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with caution. China's cultural heritage includes a large number of such earthen sites, for example the Liangzhu site in the Yangtze River basin, the Dahecu site in central China, the Sanxingdui site in the southwest, and the Western Xia imperial tombs on the Hetao Plain, as well as passes, beacon towers, castles, and sections of the Great Wall distributed across northern China [2]. These sites serve as crucial carriers for the transmission of civilization and typically preserve rich information on local history, culture, forms of social organization, and environmental evolution [3]. When exposed without adequate protection or maintenance, earth-based construction materials may show pronounced sensitivity to temperature and humidity fluctuations, salt accumulation, biological activity, wind erosion, and other environmental pressures, which poses challenges for their conservation.

The construction materials of earthen heritage sites are predominantly earth-based, the remains are often of large scale, and in most cases the structures are directly exposed at the ground surface. Their exposed soil fabric is therefore vulnerable to repeated thermal–moisture cycling, salt transport and crystallization, wind–rain erosion, and biological colonization, which can result in varying degrees of damage. For example, at the Jiaohe Ancient City site in Xinjiang, China, exposed earthen walls have developed surface spalling, cracking, and basal erosion under the combined action of salt crystallization, wetting–drying cycles, freeze–thaw cycling, wind erosion, and rainfall. These pathologies continuously remove surface materials and weaken wall stability, illustrating the vulnerability of Chinese earthen heritage sites exposed to arid and semi-arid environments [4]. In addition, extensive proliferation of microorganisms can cause severe damage in situ. Microbial activity not only alters the visual appearance of the remains, but also accelerates the mineralization processes of the earthen fabric, thereby inducing loss of earthen material [5]. On the surfaces of a number of sites exposed to the natural environment—such as the Laohuling site, the Nancheng Wall site, the Qiuwu site, the Tangshan site, and the Liyushan site—pronounced microbial corrosion phenomena have already been observed [6].

Given China's vast territory, the earthen material types and morphological forms of earthen sites are highly diverse, and the associated construction techniques are likewise complex [7]. Combined with the marked climatic contrasts between the north and the south, this leads to a wide variety of deterioration patterns in earthen heritage sites [8]. Common forms of erosion and degradation (Figure 1) include collapse, undercutting and hollowing, cracking, weathering, vegetation encroachment, water erosion, and damage caused by human activities [9], all of which pose serious threats to the long-term preservation and safe utilization of earthen heritage sites.



**Figure 1.** Deterioration of earthen heritage sites in China [10]: (A) collapse; (B) undercutting and hollowing; (C) cracking; (D) weathering.

Surface spalling (Figure 2) is the most common and most detrimental type of earthen-material deterioration in northwestern China. Spalling refers to a deterioration process in which, under the combined action of salt migration and crystallization, freeze–thaw cycling, and wetting–drying cycles, a relatively dense surface crust gradually forms on the site, accompanied by cracks that develop roughly parallel to the exposed surface. As the interface between this crust and the underlying loose earthen material progressively weakens and becomes unstable, the crust eventually detaches and falls off in laminar or blocky fragments, leading to continuous loss of surface material and progressive degradation. This type of damage persistently removes the outermost fabric of the site, causing the exposed section to become progressively thinner and accelerating the overall weathering process [11].



**Figure 2.** Current spalling conditions at the Yar City site [4].

Earthen heritage sites are constructed primarily of earth-based materials, and most are directly exposed at the ground surface. The development and evolution of their near-surface pathologies (such as spalling) are closely related to the external environment and to the material composition and properties of the earthen fabric [12]. For example, the content of soluble salts may influence the spalling of surface crusts on earthen walls [13]; the formation of gullies may be caused by runoff erosion triggered by intense rainfall [14]; and basal undercutting and erosion may be associated not only with salt accumulation, aeolian sand abrasion, freeze–thaw cycling, and precipitation, but also with capillary rise and moisture accumulation at the wall base, which can reduce interparticle cohesion and weaken the lower part of earthen walls [15].

Against the backdrop of socio-economic development and ongoing urbanization, the demand for land development and utilization continues to grow, thereby increasing the risks of encroachment, disturbance, and environmental alteration faced by earthen heritage sites. Coupled with weak awareness of earthen heritage conservation, inadequate management, and insufficient attention to the effective protection of cultural relics within these sites, these anthropogenic pressures may alter the preservation environment of earthen heritage sites and increase their vulnerability to progressive deterioration [16]. Existing studies and topic-specific reviews have provided valuable foundations for under-

standing the conservation of earthen heritage sites, including progress in the conservation of Chinese earthen sites in arid environments [17], climate-related risks to cultural heritage [18], and the development of specific protective materials or techniques, such as superhydrophobic coatings for earthen-site protection [19]. However, these studies often focus on either a particular environmental factor, a specific type of conservation material, or a limited group of case studies. Comparatively less attention has been given to an integrated synthesis that links deterioration mechanisms, coupled environmental actions, construction-technique differences, and the applicability of conservation treatments within a China-focused framework.

Based on the above research gaps, this review is guided by three main questions: (1) What are the major deterioration problems and causal mechanisms affecting earthen heritage sites in China? (2) How do regional climate, material characteristics, and construction techniques influence the manifestation of these deterioration processes? (3) Which conservation strategies are suitable for different damage types and site conditions, and what are their main limitations? Accordingly, the objective of this review is to establish a problem–mechanism–context–solution framework for understanding deterioration processes and evaluating conservation strategies for earthen heritage sites in China.

Against this background, the novelty of this review lies in four aspects. First, it focuses on earthen heritage sites in China while drawing on selected international studies where they provide useful comparative evidence. Second, it organizes deterioration mechanisms into a consistent framework covering salt-induced erosion, wetting–drying cycles, wind erosion, microbial deterioration, freeze–thaw cycles, and multifield coupling. Third, it links these mechanisms with corresponding conservation techniques, including preventive conservation, material-based protection, structural repair, and emergency stabilization. Fourth, it emphasizes the limitations of transferring laboratory findings and individual treatment methods directly to real sites, particularly under coupled environmental conditions and different earthen construction techniques. In this way, this review aims to provide a structured and critical basis for mechanism-oriented, site-specific, and preventive conservation strategies for earthen heritage sites in China.

## 2. Methodology

This review was conducted as a narrative review supported by targeted literature searches and structured thematic screening. Relevant publications were identified mainly through international academic databases and publisher platforms, including Web of Science Core Collection, Scopus, ScienceDirect, SpringerLink, and Google Scholar. The literature search was conducted from June 2025 to the final revision stage of the manuscript, and supplementary searches were carried out during the revision process to include relevant publications available at that time.

The literature search was carried out using combinations of object-related, deterioration-related, and conservation-related terms. Object-related terms included “earthen heritage site”, “earthen architecture”, “earthen wall”, “rammed earth”, “adobe”, and “cob”. Deterioration-related terms included “deterioration mechanism”, “salt crystallization”, “salt-induced erosion”, “wetting–drying cycle”, “wind erosion”, “microbial deterioration”, “freeze–thaw cycle”, “water–salt migration”, “capillary rise”, “basal erosion”, “undercutting”, and “multifield coupling”. Conservation-related terms included “preventive conservation”, “consolidation”, “hydrophobic treatment”, “protective shelter”, “backfilling”, “grouting”, “anchoring”, “microbially induced calcium carbonate precipitation”, and “emergency stabilization”. These terms were used individually and in combination to identify studies related to deterioration processes, conservation materials, and site-management strategies for earthen heritage.

The inclusion criteria were as follows: (1) studies focusing on earthen heritage sites, earthen architecture, or earth-based archeological remains; (2) studies addressing deterioration mechanisms caused by environmental or anthropogenic factors, such as salt, moisture, wind, microorganisms, freeze–thaw action, human activity, or coupled effects; (3) studies reporting conservation, stabilization, reinforcement, emergency intervention, or preventive protection measures for earthen heritage sites or comparable earthen materials; and (4) studies providing experimental, field-monitoring, case-study, or theoretical evidence relevant to the conservation of earthen heritage. Publications were excluded when they focused only on modern earth construction without a clear heritage-conservation context, general geotechnical soil behavior without relevance to earthen heritage, unrelated building materials, or studies lacking sufficient methodological or technical information.

The retrieved literature was screened in three steps. First, titles and abstracts were reviewed to remove clearly irrelevant publications. Second, potentially relevant papers were examined in full to determine whether they met the inclusion criteria. Third, the selected literature was grouped according to deterioration factors, conservation approaches, construction techniques, and relevance to earthen heritage sites in China. Because this review focuses primarily on Chinese earthen heritage sites, Chinese case studies and conservation practices reported in the accessible literature were emphasized. Selected international studies were included where they provided useful comparative evidence, methodological reference, or broader conservation context. The final synthesis followed a problem–mechanism–context–solution framework rather than presenting the literature as a simple sequence of individual studies. Under this framework, the review first identified the main deterioration problems and damage forms, then analyzed their causal mechanisms and regional, climatic, material, or constructional contexts, and finally evaluated the corresponding conservation strategies in terms of evidence basis, suitability, and limitations. This framework was used to connect single-factor deterioration, multifield coupling, preventive conservation, emergency stabilization, and practical conservation decision-making in a coherent analytical structure.

### 3. Deterioration Mechanisms

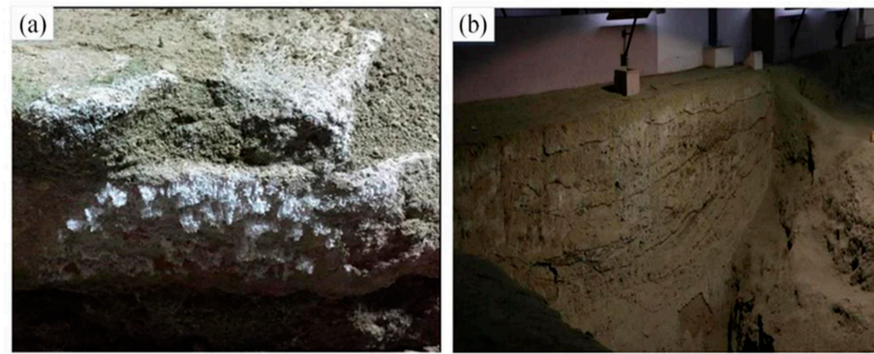
The long-term stability of earthen heritage sites is controlled by the interaction among material composition, construction technique, environmental exposure, and maintenance conditions. When exposed for long periods to temperature variation, moisture fluctuation [9], salinity [20], biological colonization, including algal growth and microbial communities on or within earthen relics [21,22], acidity–alkalinity conditions [23], and mechanical or loading-related disturbances, such as cyclic loading and vibration effects [24], earthen structures may undergo progressive deterioration. Therefore, the transition from localized damage to larger-scale instability should be understood not simply as a result of insufficient intrinsic strength, but as the outcome of interactions among material properties, environmental actions, structural form, and conservation history [25]. In response to this central issue, many scholars have conducted in-depth studies on the engineering properties of earthen heritage sites [26]. With the application of advanced techniques such as portable digital microscopy and scanning electron microscopy (SEM), as well as visual assessment and 3D laser scanning, the key factors governing the stability of earthen sites and their underlying mechanisms have gradually become clearer [27]. To maintain a consistent classification throughout this review, the deterioration mechanisms are discussed according to six main categories: salt-induced erosion, wetting–drying cycles, wind erosion, microbial deterioration, freeze–thaw cycles [28], and multifield coupling. In this framework, weathering is not treated as a separate category, but as a general manifestation or outcome of

several deterioration processes, such as salt crystallization, wetting–drying cycles, wind erosion, and freeze–thaw action.

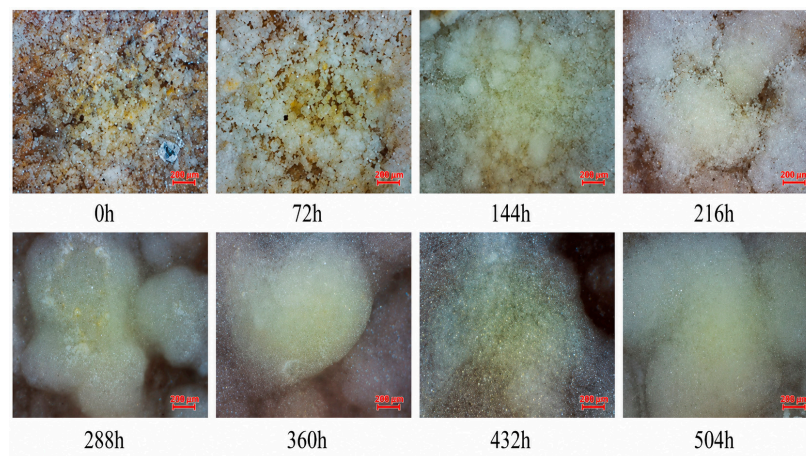
It should also be emphasized that these deterioration mechanisms do not occur with the same intensity or in the same form across all earthen heritage sites in China. China contains markedly different climatic regions, ranging from arid and semi-arid areas in the northwest to cold regions with frequent freeze–thaw action and humid or seasonally wet regions affected by rainfall and biological activity. In arid and semi-arid environments, salt migration, salt crystallization, wind erosion, and basal erosion are often prominent, whereas in cold regions freeze–thaw cycling may become a major driver of cracking and strength loss. In humid or seasonally wet regions, rainfall erosion, wetting–drying cycles, moisture accumulation, and microbial deterioration may play more important roles. In addition, different construction techniques, such as rammed earth, adobe or earthen-block masonry, cob, earthen renders or plasters, and wattle and daub, may respond differently to the same environmental stress because of differences in compaction state, pore structure, joints, organic additives, and moisture-transport pathways. Therefore, the deterioration mechanisms discussed below should be understood as regionally and constructionally dependent rather than universally identical across all Chinese earthen heritage sites.

### 3.1. Salt-Induced Erosion

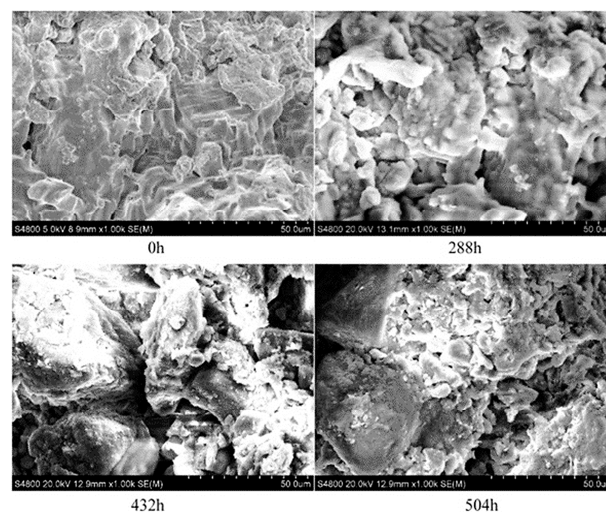
One of the pressing issues in the conservation of earthen heritage sites is the accumulation of soluble salts on the site surface caused by water migration and evaporation (Figure 3). This phenomenon is also a common and primary cause of drying cracks and weathering damage in such sites [20]. The main driving force for the migration of liquid water within earthen sites is capillary action. It should be distinguished that capillary rise first represents a hydraulic moisture-transport and weakening process: even before salt crystallization occurs, moisture accumulation can soften the earthen fabric, reduce inter-particle cohesion, and promote basal erosion or particle detachment. Evaporation reduces the moisture content of the near-surface earthen material, thereby enhancing capillary forces; as a result, liquid water in deeper layers of the earthen body transports dissolved salts upward under capillary action, ultimately leading to salt accumulation in the near-surface zone [29,30]. Salt accumulation can induce surface powdering and cracking of earthen remains, as exemplified by the deterioration of the earthen walls at the Bianguan Fort site [29] and the degradation observed in the K9901 burial pit at the Qin Emperor's Mausoleum Museum site [31]. Han W et al. [29] collected rammed-earth samples from the walls of the Bianguan Fort site and conducted salt-solution erosion tests to simulate the process of salt migration. Using a portable digital microscope and scanning electron microscopy (SEM), they examined the morphological evolution of salt crystals and the surfaces and interiors of the rammed-earth specimens. Observations of the surfaces of compacted foundation samples at 200× magnification (Figure 4) revealed a systematic change in salt crystals with the duration of salt supply: in the early stage (0–72 h), the crystals were few in number, small in size, and uniformly distributed; with increasing time, the crystals gradually aggregated and coarsened; between 432 and 504 h, the crystal size showed no obvious change and remained uniformly distributed; and by 504 h, salt precipitation reached saturation and covered the entire sample surface. In contrast, SEM observations at 1000× magnification of specimens from the interior of the rammed earth (Figure 5) showed that at 0 h the soil particles were tightly bonded and the pores were small; as the duration of salt supply increased, the pores enlarged, reaching a maximum at 288 h (approximately one-third of the size of adjacent soil particles), at which time powdering and efflorescence were most severe. By 504 h, although the pores had decreased in size due to infilling by soluble salts, they remained larger than those at 0 h.



**Figure 3.** Salt-induced deterioration of earthen heritage sites [32]. (a) Jiangnanguan Street Tang–Song settlement site in Chengdu; (b) Banpo site.



**Figure 4.** Micromorphology of salt crystals on the surface of rammed earth at 200× magnification [29].



**Figure 5.** Observations of the micromorphology of rammed-earth samples and salt crystals using a portable digital microscope and scanning electron microscopy (SEM) [29].

Salt accumulation can also induce crystallization pressure within the earthen body. When salts within the earthen fabric undergo repeated cycles of crystallization and dissolution, their volume changes accordingly. Under the recurrent action of expansion and contraction, the earthen structure gradually becomes loosened, eventually leading to structural damage of the earthen body [33].

Zhang Y et al. [4] investigated the Jiaohu Ancient City site and, through unsaturated soil mechanics tests, found that salinity can increase the total suction via osmotic pressure,

thereby accelerating moisture migration and the accumulation of shrinkage stress. Cycles of salt crystallization and dissolution induce volumetric changes and structural disruption in the earthen fabric, revealing the critical roles of suction and salt crystallization in the surface cracking and deterioration of earthen heritage sites.

### 3.2. Wetting–Drying Cycles

Coupled environmental actions, such as wetting–drying cycles, can induce cracking in the earthen body, reduce structural integrity and strength, and thus cause significant damage to earthen remains [34]. In natural environments, most soils undergo wetting–drying cycles, during which their strength and deformation characteristics are continuously altered. For earthen sites located in humid environments, high moisture contents tend to undermine their stability; in contrast, under dry conditions the soil moisture content decreases, and the shrinkage that occurs during desiccation generates cracks that severely compromise the integrity of the earthen material and consequently reduce its strength [35]. With an increasing number of wetting–drying cycles, existing cracks in the earthen material continue to propagate while new cracks are generated [36]. To mitigate the damage induced by wetting–drying environments to earthen remains, it is therefore essential to conduct in-depth studies on the strength and deformation behavior of earthen materials subjected to wetting–drying cycles [37].

Dong M et al. [34] investigated the silty clay from the Laohuling dam at the Liangzhu archeological site and, by simulating different numbers of wetting–drying cycles for comparison, found that as the number of cycles increased, pre-existing cracks in the soil progressively extended while new cracks were initiated, thereby impairing soil integrity and reducing strength. Meanwhile, these newly formed fractures act as preferential pathways for rainfall infiltration, leading to higher degrees of saturation in the soil and attenuation of matric suction, which in turn exerts adverse effects on the strength behavior of the soil [38]. Mercury intrusion porosimetry (MIP) test results indicate that, in soils subjected to wetting–drying cycles, the proportion of large pores increases significantly [39]; their pore-size distribution is primarily governed by the cycling process, with pore diameters mainly in the range of 5–250  $\mu\text{m}$  [40]. Scanning electron microscopy (SEM) observations further show that wetting–drying cycles loosen the earthen fabric and induce microcracks, while weakening the contacts between soil particles [41].

### 3.3. Wind Erosion

When earthen heritage sites are exposed to natural environments over long periods, they are highly susceptible to wind erosion. Wind-borne sand particles abrade and impact the surfaces of the structures, causing loss of earthen particles and changes in surface morphology, which in turn reduces the stability of the earthen structure [42]. It should be noted that wind erosion does not affect all parts of an earthen wall in the same way. Direct wind-induced abrasion is usually most pronounced at exposed and geometrically discontinuous parts, such as wall tops, edges, corners, openings, and windward surfaces, where airflow acceleration and sand-particle impact are more intense. By contrast, basal erosion and undercutting are generally not caused by wind action alone. At wall bases, capillary rise, moisture accumulation, salt crystallization, rainfall runoff, or freeze–thaw action may first reduce cohesion and weaken the earthen fabric; wind-blown sand can then further abrade the already weakened material and accelerate basal material loss. Therefore, wind erosion should be understood as a direct agent for wall-top and edge abrasion, and as a contributing or amplifying factor in basal undercutting when it acts together with moisture- and salt-related deterioration processes.

Wind erosion events cause material loss in earthen heritage sites, and because they occur frequently, their cumulative effects are highly significant [43]. The key zones of wind-induced erosion are concentrated at geometric discontinuities [43], such as wall corners, edges, and tops. The extent of undercutting on the windward side is markedly greater than that on the leeward side, and walls oriented at an angle of about 30° to the prevailing wind direction suffer the most severe undercutting [44]. On windward walls [45], wind erosion leads to extensive surface polishing and pitting, and the wall corners become progressively rounded. Concentrated erosion is particularly likely to occur at joints and cracks in the wall. In addition, wind erosion reduces the vertical height and horizontal thickness of the wall, producing a typical “top-wide, bottom-narrow” degradation profile [43], which may further develop into surface spalling, undercutting, and even collapse.

Chen W et al. [46] further found that wind-blown sand not only erodes the wall surfaces but also causes sand to accumulate on both sides of the walls. Using computational fluid dynamics (CFD) to simulate the trajectories and accumulation of sand particles, and combining this with UAV-based modeling to construct a three-dimensional model of the Suoyang Ancient City site, they reconstructed the wind–sand interactions under the site’s complex topography and simulated the patterns of wind-blown sand movement and deposition. The results showed that wind speed over the wall tops and at openings can be amplified by a factor of 1.5, thereby intensifying erosion. In addition, airflow on the windward side is relatively stable and sand accumulates uniformly, whereas on the leeward side turbulence generates a “recirculation zone,” where sand forms an arcuate accumulation pattern.

### 3.4. Microbial Deterioration

The metabolic activities of microorganisms may lead to surface spalling and structural damage of earthen materials, and can also accelerate mineralization by consuming organic matter, thereby causing loss of earthen material. In addition to bacteria and algae, fungi should also be considered an important agent of biological deterioration. Fungal colonization in biofilms on earthen surfaces may lead to discoloration, surface alteration, and material weakening, and has been reported in different forms of earthen architecture, including adobe, wattle and daub, and rammed earth [47]. In earthen sites, members of the phyla Proteobacteria and Actinobacteria can, through their metabolism, produce pigments, organic acids, and polysaccharides [21], which result in damage to the soil structure and corrosion of the surface. Acidophilic bacteria [48] degrade organic matter, rendering the earthen structure looser and consequently threatening the stability of the site. Photosynthetic microorganisms [48] provide organic substrates for other microbes, promoting their growth and reproduction, which in turn further exacerbates surface erosion of the heritage site.

The activity of microorganisms is strongly influenced by environmental factors. Studies have shown that soil temperature and air temperature are key drivers of changes in microbial community structure, and within a certain range, increasing temperature generally enhances microbial activity [49]. Variations in environmental parameters such as soil moisture content and salinity also markedly affect the composition of bacterial and eukaryotic communities; however, the specific relationships differ among sites and climatic settings [48,49]. Seasonal succession has a more pronounced impact on bacterial communities of prokaryotes, whereas its effect on eukaryotic communities is comparatively weaker [48].

### 3.5. Freeze–Thaw Cycles

Under freeze–thaw action, the internal temperature distribution and water flow regime within earthen heritage sites change significantly. The coupled processes of water–salt–heat

transfer drive repeated solid–liquid phase transitions, crystallization, and dissolution of water and salts in the pores, leading to expansion of the pore structure and softening of the earthen skeleton. Consequently, key physical and mechanical parameters of earthen materials, particularly rammed earth in the experiments summarized here, such as water content, bulk density, porosity, permeability, and shear strength, are altered. Meanwhile, the continuous migration, crystallization, and dissolution of soluble salts within rammed-earth structures induce salinization, thereby reshaping their shear strength and other geotechnical properties [50]. It should be noted that the response of other earthen construction techniques, such as adobe or earthen-block masonry, may differ from that of rammed earth because of differences in compaction state, block interfaces, pore structure, and material composition; therefore, conclusions derived from rammed-earth studies should be extended to other earthen construction forms with caution. Existing studies have clearly demonstrated that snowfall can trigger freeze–thaw cycles coupled with salinization to varying degrees, and that this coupled process damages rammed-earth structures [51], constituting an important cause of deterioration in earthen heritage sites.

The coupled effects of freeze–thaw cycles and salinization drive repeated expansion and contraction of rammed earth [50], not only generating new cracks and reactivating closed microcracks, but also increasing permeability and weakening the cohesion between soil particles. Once the microstructure of the rammed earth is damaged, its hydraulic properties, mechanical strength, and resistance to wind and rain erosion all deteriorate [52]. These changes in material properties create favorable conditions for the development of such pathologies as basal undercutting and hollowing, surface crusting, and even structural collapse.

### 3.6. Multifield Coupling

Current research mostly focuses on single-factor or two-factor coupling, whereas genuine multifield coupling has been much less studied. Guo Q et al. [53], working in the Multifield Coupling Laboratory of the Dunhuang Academy, conducted weathering simulation tests on large sandstone blocks under combined conditions of rainfall, temperature, and solar radiation. The results showed that, under the same rainfall intensity and duration, an increasing number of tests led to shorter times to the onset of runoff and smaller runoff volumes, while rainfall penetration depth and average water content increased; internal damage within the sandstone continued to expand, and rainfall became more prone to infiltration and evaporation (Table 1). In summer, when the sandstone is simultaneously subjected to rainfall, elevated temperature, and sunlight, its weathering is governed mainly by chemical water–rock interactions, including mineral hydrolysis, oxidation, hydration, salt crystallization cycles, and tensile stresses induced by temperature variations; the combined action of these processes ultimately drives the weathering of the sandstone.

**Table 1.** Infiltration characteristics under the same rainfall intensity with sequential loading of working conditions [53].

| Working Conditions | Rainfall Intensity (mm/h) | Duration (min) | Rainfall (mm) | Time of the Runoff Generation (s) | Runoff Amount (L) | Average Infiltration Depth (mm) | Average Water Content (%) |
|--------------------|---------------------------|----------------|---------------|-----------------------------------|-------------------|---------------------------------|---------------------------|
| Condition 1        | 20                        | 60             | 20            | 300                               | 1.45              | 18.68                           | 2.04                      |
| Condition 2        | 60                        | 50             | 50            | 100                               | 5.46              | 45.05                           | 2.83                      |
| Condition 3        | 20                        | 60             | 20            | 220                               | 1.20              | 18.91                           | 2.58                      |
| Condition 4        | 60                        | 50             | 50            | 90                                | 6.11              | 45.12                           | 3.74                      |

### 3.7. Limitations of Current Research and Priorities for Future Studies

Overall, the mechanisms of individual factors—such as salt-induced deterioration, wetting–drying cycles, wind erosion, microbial deterioration, and freeze–thaw cycles—have been relatively well studied, but many conclusions are derived under controlled laboratory conditions and still differ from in situ behavior at heritage sites. In studies of salt damage, single salts and fixed temperature–humidity conditions are commonly adopted, whereas real sites are usually characterized by mixed-salt and multi-ion environments with diurnal temperature and humidity fluctuations; as a result, the locations of salt crystallization and the morphology of surface crusts may change, which in turn affects whether spalling occurs and when it occurs [54]. In wetting–drying research, many tests are conducted using fixed cycles of soaking and oven-drying, but in the field short-duration rainfall events followed by strong evaporation are more typical. Thus, even with the same number of cycles, differences in ventilation and evaporation conditions may lead to markedly different crack patterns and surface deterioration outcomes [35]. In wind-erosion studies, site morphology and wind-field conditions are often simplified to facilitate calculation and comparison, and the resulting findings do not necessarily explain long-term wind-regime changes over complex topography very well [43]. Although studies on microbial deterioration can reveal differences in microbial community composition among areas with different types of damage and their relationships with environmental factors such as temperature, humidity, and salinity, there is still a lack of direct evidence demonstrating how key metabolic processes weaken cementation, alter pore structures, and drive salt damage or spalling, and more explicit mechanistic verification is needed [49]. In freeze–thaw studies, the process is often summarized simply in terms of the number of cycles, while the effects of details such as cooling rate, thawing path, and moisture state on the damage evolution are frequently downplayed [26]. Looking further, although research on multifield coupling is increasing, most work still remains at the level of listing single-factor mechanisms side by side, and a clear explanatory framework is lacking for how multiple factors interact and how different forms of damage successively propagate. Therefore, future studies need to be carried out under boundary conditions that more closely approximate those of real sites, with closer integration of field monitoring, experiments, and modeling, in order to reduce the discrepancy between experimental conclusions and in situ behavior and thereby provide a more reliable basis for the long-term conservation of earthen heritage sites [55]. In particular, in situ testing and long-term field monitoring are essential for verifying whether mechanisms identified under well-controlled laboratory conditions remain valid under the complex boundary conditions of real earthen heritage sites.

## 4. Conservation Techniques for Earthen Heritage Sites

To strengthen the alignment between deterioration mechanisms and conservation treatments, the conservation techniques reviewed in this section are organized according to the mechanism-oriented logic established in Section 3. In this framework, salt-induced erosion is mainly addressed through moisture control, salt migration inhibition, and surface protection; wetting–drying damage is addressed through hydrophobic treatment, material modification, and compatibility improvement; wind erosion is addressed through surface consolidation and anti-weathering protection; microbial deterioration is addressed through biological inhibition and environmental regulation; freeze–thaw-related damage is mainly mitigated through moisture control, drainage improvement, and compatible consolidation; and multifield coupling requires integrated strategies combining monitoring, drainage, material protection, structural reinforcement, and site-specific maintenance. Therefore, the following discussion links each conservation measure to the deterioration

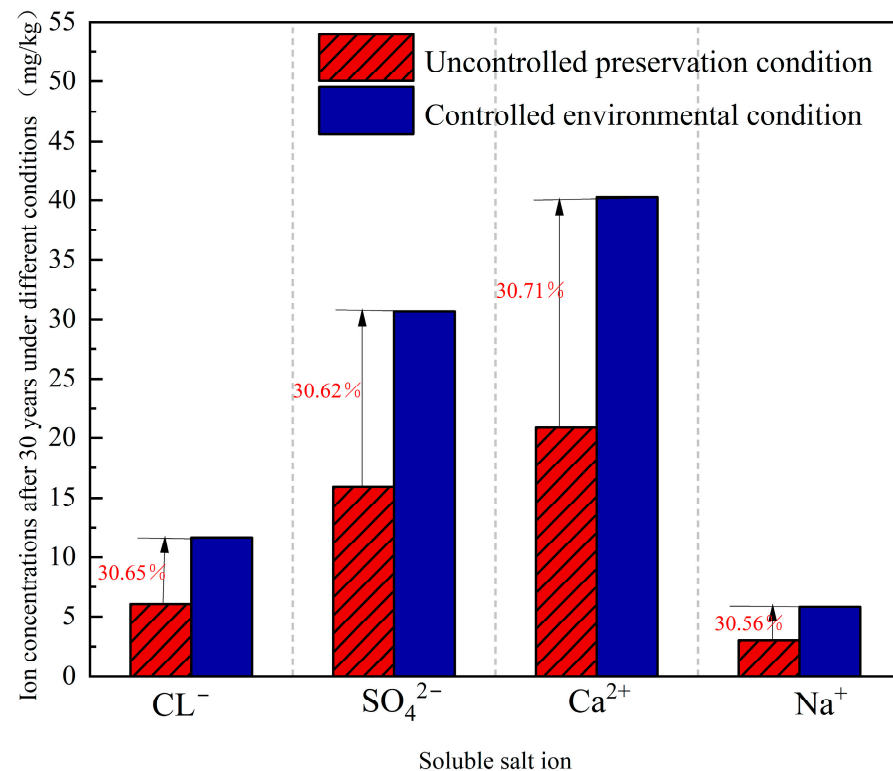
problem it is intended to control, rather than presenting the techniques as independent or sequential examples.

Due to the lack of appropriate conservation measures, most earthen heritage sites have to be reburied after excavation [56]. For those areas that are not backfilled but instead left exposed and opened to the public, protective shelters are typically erected in situ to shield them from climatic damage. However, this mode of preservation also gives rise to a series of new challenges. Prior to excavation, the earthen materials of most earthen sites generally have a relatively high moisture content; once exposed to the atmosphere, moisture evaporates rapidly [57]. Although protective shelters can prevent direct weathering and erosion, they also impede the replenishment of moisture, resulting in a predominantly unidirectional migration of water (evaporation) within the earthen body. This, in turn, induces shrinkage and cracking of the heritage fabric, as well as surface salt weathering. In addition, repeated dissolution and crystallization of soluble salts can lead to surface powdering of the site. To maintain the structural integrity of earthen remains, consolidants are commonly used in engineering practice, including organic consolidants such as acrylic resins, silica sol, and ethyl silicate [9], as well as inorganic consolidants such as inorganic silicates and limewater [58]. However, organic consolidants are often characterized by limited service life and poor compatibility with the original fabric; inorganic consolidants, while generally offering longer durability and better compatibility, tend to have limited penetrability and may promote the formation of salts. These issues not only threaten the authenticity of earthen heritage sites but may also cause secondary damage to the site fabric [59].

By gaining an in-depth understanding of the dynamics of wind-blown sand, targeted preventive measures can be adopted in the conservation of earthen sites—for example, local reinforcement at openings and elevated portions, and the installation of vegetation or mechanical barriers upstream along the prevailing wind direction to reduce wind speed and thereby diminish sand transport [46]. Xia Y et al. [31] took the K9901 burial pit at the Qin Emperor's Mausoleum Museum as a case study and monitored water and salt variations at different soil depths through soil column experiments, in order to elucidate the dynamic processes of water–salt migration and salt accumulation within the earthen site. Their results indicate that salt accumulation is a key factor driving the deterioration of the Qin Mausoleum earthen remains, and that environmental control is an effective means of mitigating salt damage. Under controlled environmental conditions with a temperature of 13–17 °C and relative humidity of 62–68%, the salt concentration can be reduced by more than 30% compared with uncontrolled conditions, significantly slowing the progression of salt-induced deterioration (Figure 6).

China's efforts to conserve earthen heritage sites can be traced back to the 1920s and have since yielded substantial practical achievements. In the field of earthen-site conservation, research teams have carried out systematic studies on strengthening techniques, preventive conservation strategies, and reinforcing materials. They have not only formulated national and industry standards for the conservation of earthen heritage sites, but have also established a technical system encompassing such procedures as compaction-based strengthening [60], anchorage support [61], crack grouting [62], and surface anti-weathering treatments [63]. These techniques have been widely applied in conservation projects for earthen sites in arid regions and are also being explored in conservation practice under humid environmental conditions. Based on the deterioration types of earthen sites and their environmental characteristics, classification systems for deterioration in arid and humid environments have been developed, together with corresponding monitoring techniques. In the area of novel protective materials, a series of innovative products have been successfully developed, including PS consolidants [64], cement grouts incorporating calcined plant ash [65], SH-based reinforcement treatments [66], calcium-based liquid hydraulic

hardeners [67], inorganic bonding materials [68], and organosilicon-modified acrylic resin non-aqueous dispersions [69]. These research outcomes have already been implemented in conservation projects at more than 200 nationally designated key cultural relic protection units across China, providing a solid foundation for the safe safeguarding and appropriate utilization of numerous valuable cultural heritage sites, and directly supporting the nomination of several properties for inscription as World Cultural Heritage.



**Figure 6.** Comparison of salt-ion accumulation in earthen materials under two different conservation modes [30]. (The arrows indicate the percentage change between uncontrolled preservation conditions and controlled environmental conditions, and the dashed vertical lines are used to separate different ion species).

#### 4.1. Targeted Conservation Techniques for Single Environmental Factors

A systematic investigation of the deterioration mechanisms of earthen heritage sites, followed by the implementation of targeted conservation measures, is of decisive importance for the scientific preservation of these sites.

##### 4.1.1. Techniques for the Prevention and Control of Salt Damage

At present, conservation efforts for earthen heritage sites have been further extended to include multiple aspects such as structural repair, prevention and control of salt-related damage, and sacrificial-layer protection [63]. However, salts within earthen sites migrate primarily with water; only by blocking the upward movement of water carrying dissolved salts toward the site surface and establishing a barrier zone to water–salt migration can the harmful effects of salt accumulation be fundamentally eliminated. Xu W et al. [32] took the Terracotta Warriors earthen site as their research object and investigated the effectiveness of hydrophobic plastic-coated sand in blocking water–salt migration, verifying its performance through experiments and numerical simulations. Their results showed that the coated sand can effectively prevent water–salt migration induced by groundwater and precipitation, completely blocking water–salt migration in both the vertical and horizontal directions and thus forming a “safe zone.” In this way, it prevents damage to the site

caused by salt accumulation and provides a new method for the conservation of earthen heritage; nevertheless, the blocking performance of the coated sand under extreme rainfall conditions still requires further verification. Chang B et al. [70] proposed a novel anti-salt technology based on the theory of water–salt migration in unsaturated soils, in which a sand layer is placed beneath the remains to act as a water–salt barrier. This technique exploits the relatively large inter-particle voids in the sand layer to reduce capillary forces and block the upward migration of water and salts from deeper soil layers. By varying the grain size of the sand layer and simulating water–salt migration behavior, experiments demonstrated that the sand layer can effectively confine water and salts to the bottom boundary, preventing salt accumulation at the surface of the remains; moreover, the larger the sand grains, the more pronounced the water–salt barrier effect. These findings confirm that using a sand layer as a water–salt barrier is an effective and sustainable method for protecting earthen remains from salt damage.

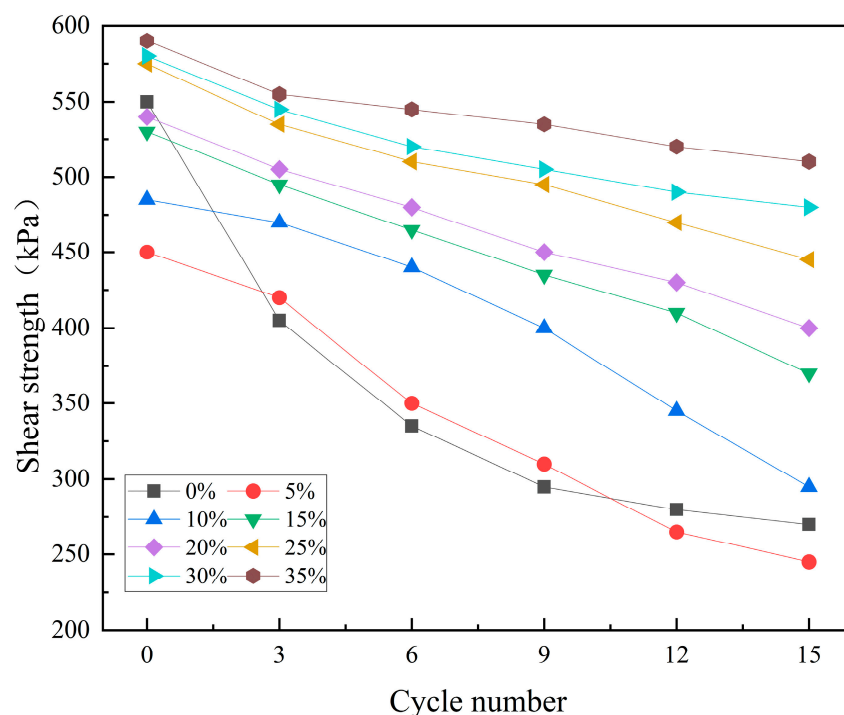
Water–salt migration is a key factor driving the development of basal erosion in earthen heritage sites and poses a serious threat to their conservation; therefore, studies aimed at interrupting or altering water–salt migration pathways are of great significance. Polyvinyl alcohol (PVA)-modified earthen materials with pronounced hydrophobicity have shown promising potential for use as moisture-proof sublayers. Zhang Q et al. [71] reported that when the PVA content in the earthen material does not exceed 1.0%, the addition of PVA does not cause noticeable color changes and, although it reduces water-vapor permeability to some extent, the wall can still maintain its basic capacity for vapor dissipation under appropriate mix proportions and construction conditions. This indicates good compatibility between PVA and earthen heritage materials. The incorporation of PVA into earthen materials significantly enhances their hydrophobicity and strength [72]. Zhang Q et al. [73] further found that when a hydrophobic PVA sublayer is laid continuously beneath the entire base of an earthen wall, soluble salts are unable to migrate upward into the upper parts of the wall, thereby preventing basal erosion and demonstrating that a PVA sublayer can effectively suppress such erosion. In contrast, when the hydrophobic sublayer is only partially laid, it can reduce solute concentrations at the wall base to some degree, but even with a sublayer length of 30 cm, the reduction in concentration remains limited. This suggests that full-coverage installation of a hydrophobic sublayer beneath the wall base is necessary. With regard to the laying direction, the hydrophobic sublayer should extend upward along the inner side of the wall rather than outward into the ground outside the wall. This configuration alters the water–salt migration pathway, causing soluble salts to accumulate in the ground outside the wall rather than at the bottom of the sublayer, thus fundamentally preventing the occurrence of basal erosion.

#### 4.1.2. Mitigation Techniques for Wetting–Drying Cycles

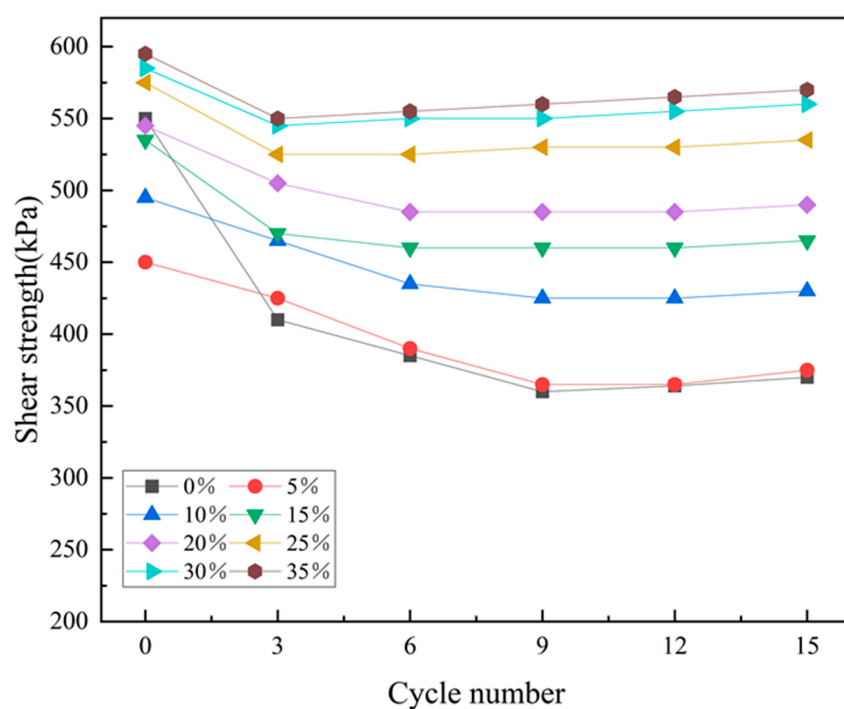
Under continuous cycles of rainfall and air drying, the physical properties of earthen materials change markedly, posing a serious threat to the stability of reinforced sites [74]. Therefore, conducting conservation studies on earthen heritage sites under wetting–drying cycle conditions is of great practical significance [75].

Under repeated wetting–drying and freeze–thaw conditions, earthen heritage sites are vulnerable to erosion-induced strength loss and structural deterioration. Calcined plant ash or biomass materials exhibit cementing effects and can effectively enhance the strength of earthen materials, providing a new feasible pathway for the conservation of earthen sites. Li Q et al. [76] demonstrated that calcined plant ash can improve the erosion resistance of site loess under wetting–drying (Figure 7) and freeze–thaw (Figure 8) conditions. Zhang Q et al. [66] investigated the feasibility of using a modified polyvinyl alcohol (SH) solution for the conservation of the Subashi Buddhist Temple site, focusing on

the impregnation and consolidation performance of the solution in coarse-grained soils. Their results showed that SH-treated coarse-grained soils exhibit good resistance to damage induced by wetting–drying cycles.



**Figure 7.** Variation in shear strength with the number of wetting–drying cycles under 400 kPa [76] (the higher the CGN dosage, the smaller the strength loss of the specimens after the same number of cycles).



**Figure 8.** Variation in shear strength with the number of freeze–thaw cycles under 400 kPa [76] (the higher the CGN dosage, the earlier the inflection point appears, and the more pronounced the subsequent strength enhancement).

#### 4.1.3. Wind Erosion Protection Techniques

For earthen heritage sites exposed to arid and semi-arid environments, wind erosion and surface weathering are key factors contributing to material loss and structural instability. Therefore, techniques for anti-weathering protection and reinforcement of earthen sites have become an important research focus in cultural heritage conservation [77].

To enhance the conservation performance of earthen heritage sites in arid, weathering-prone environments, Zhang Y et al. [78] conducted systematic studies on the inorganic chemical agent potassium silicate ( $K_2SiO_3$ , hereafter referred to as PS). Indoor wind-erosion simulation tests showed that the wind-erosion resistance of earthen specimens treated with high-modulus PS solutions was significantly improved. Wind-tunnel test results indicated a positive correlation between wind speed and the amount of wind-eroded earthen material, whereas treatment with PS solutions effectively enhanced the resistance of the earthen material to wind erosion. Although higher wind speeds led to an increase in the wind-erosion modulus, specimens treated with 5% and 7% PS solutions exhibited much smaller increases in wind-erosion modulus, and thus greater resistance to wind erosion; in particular, when wind speeds exceeded 15 m/s, the wind-erosion resistance of these specimens was approximately 6–10 times that of the untreated specimens (Figure 9). Li L et al. [79] developed a potassium silicate (PS) solution that can effectively improve the internal structural properties of site earthen materials and thereby mitigate environmental damage. PS-treated earthen materials exhibit excellent mechanical strength and wind-erosion resistance, and are able to maintain stable performance even under repeated freeze–thaw cycles.

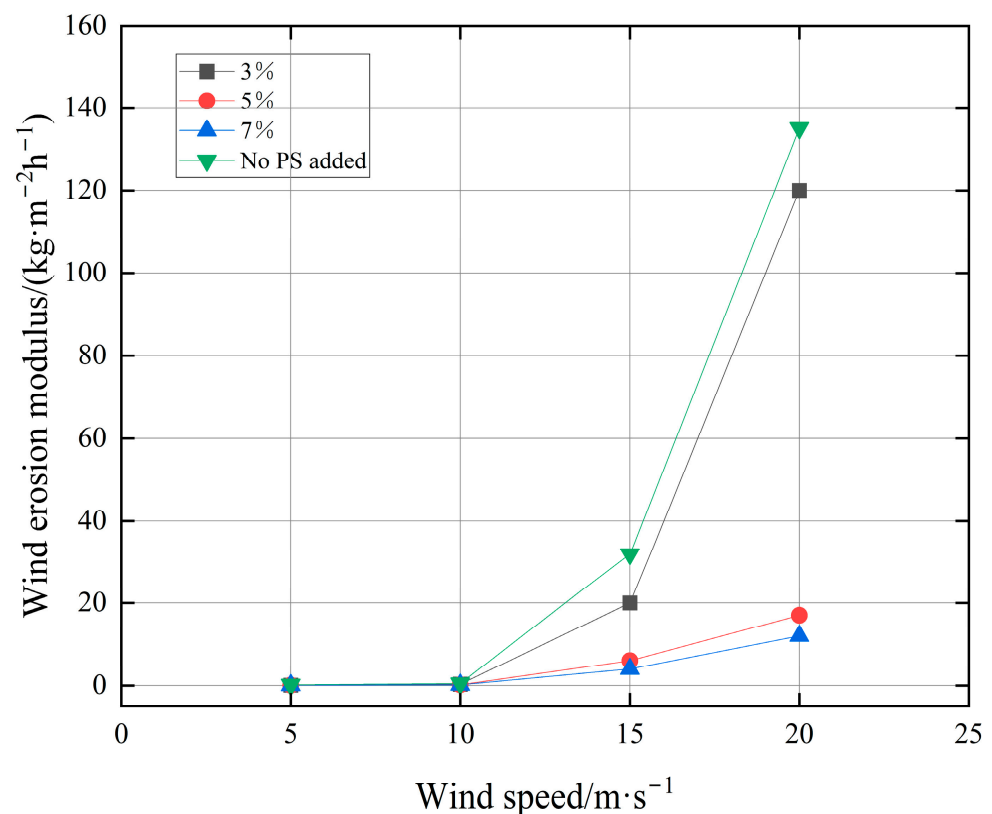


Figure 9. Comparison of wind erosion loss for differently reinforced earthen specimens [78].

Research on consolidants for earthen-site materials has made rapid progress in practical applications. Zhao D et al. [80] examined the feasibility of applying the BS-10 series of reinforcing materials (an organosilicon-modified acrylic resin emulsion, hereafter referred

to as modified acrylic emulsion) in heritage conservation projects. The results showed that, after consolidation with this material, the wind-erosion resistance of earthen-site materials was greatly enhanced, with the wind-erosion modulus reduced by a factor of 5–8 compared with the untreated state. Microscopic observations revealed that a dense mesh-like structure formed within the earthen material. Although the permeability decreased markedly, the material still maintained the capability for moisture exchange between the interior and exterior, and exhibited excellent anti-aging properties. Consequently, its resistance to wind erosion was significantly improved, and the BS-10 material can meet the reinforcement needs of certain earthen sites in arid regions.

If moisture evaporation from earthen heritage sites can be effectively slowed and their water-retention capacity enhanced, water loss from earthen materials can be substantially reduced and wind-induced damage to the sites correspondingly mitigated. Hydrogels possess a unique three-dimensional network structure that enables them to swell rapidly upon water absorption and store large amounts of water; when ambient humidity decreases, they can gradually release the stored water and thereby help maintain moisture in the earthen material. Once incorporated into the earthen material, the swelling–shrinkage behavior of the gel helps alleviate damage associated with soil wetting and drying, and the SAP (superabsorbent polymer) gel in particular exhibits outstanding performance in improving soil water retention. Zheng Y et al. [81] investigated the effects of different concentrations of superabsorbent resin (SAP) on the water-holding capacity, physical properties, and color compatibility of soils from earthen heritage sites, and treated soils from sites with varying degrees of weathering using SAP. Their results showed that SAP-2 (diluted two-fold) can markedly enhance the soil's water-holding capacity, increase its moisture content, and suppress the precipitation of soluble salts. In addition, this material has only a minor impact on material color and can enhance interparticle cohesion by filling pores in the earthen material, effectively inhibiting crack propagation and thereby improving the weathering resistance of earthen heritage sites.

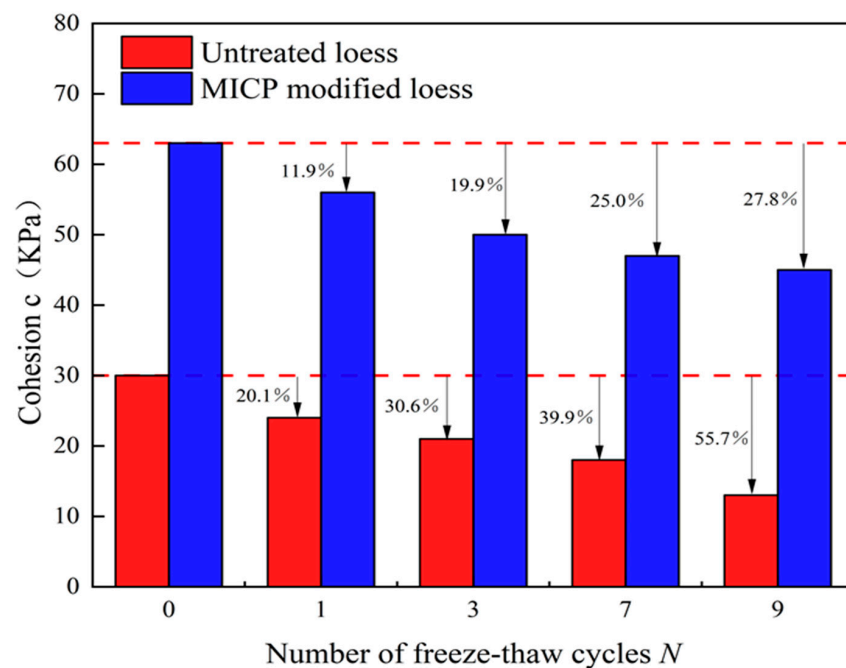
Earthen heritage sites suffer damage under persistent wind erosion, posing severe challenges for their conservation. Nevertheless, these research findings provide a scientific basis for formulating wind-erosion mitigation strategies in the conservation of earthen heritage sites.

#### 4.1.4. Techniques for Microbial Inhibition

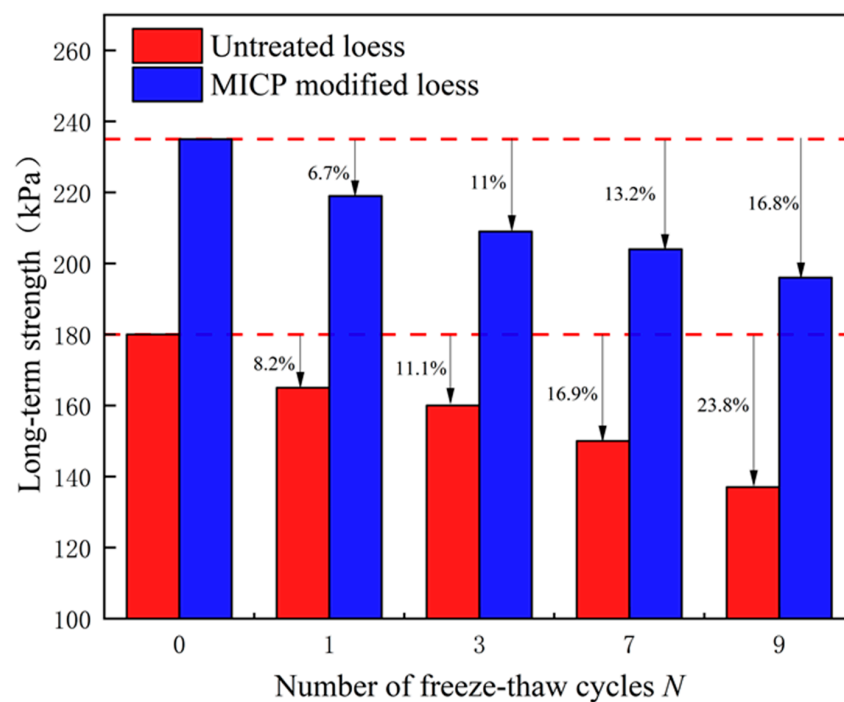
Microorganisms are among the key factors driving the deterioration of cultural heritage [82]. Although the biochemical erosion of earthen heritage sites by microorganisms threatens their long-term stability, in-depth research on microbial processes has opened up a new direction: employing microbially mediated reactions for the conservation of heritage sites [83].

Taking loess sites in northwestern China as an example, which have long been subjected to damage from freeze–thaw cycles, Liu J et al. [84] collected typical loess samples from Lanzhou and conducted multiple freeze–thaw cycle tests by incorporating bacterial suspensions and cementation solutions, in order to evaluate the protective effectiveness of microbially induced calcium carbonate precipitation (MICP) technology. The experiments showed that MICP, through the filling, cementation, and encapsulation effects of precipitated calcium carbonate, can significantly enhance the shear strength, cohesion (Figure 10), and long-term strength (Figure 11) of the loess. Under freeze–thaw conditions, MICP-modified loess exhibits excellent freeze–thaw durability. This finding provides an innovative bio-reinforcement method for the conservation of loess sites in seasonally frozen regions and opens up a new pathway for protecting other sites exposed to similar long-term freeze–thaw problems. Nevertheless, despite the considerable potential of MICP technol-

ogy for reinforcing earthen heritage sites, its practical application still requires addressing issues such as cost control and optimization of bacterial survival, and further in situ tests are needed to verify its suitability and long-term performance.



**Figure 10.** Variation in cohesion of untreated loess and MICP-modified loess under cyclic freeze–thaw conditions [84]. (The arrows indicate the percentage reduction in cohesion after freeze–thaw cycles compared with the initial value, and the dashed red lines indicate the initial cohesion values of untreated loess and MICP-modified loess before freeze–thaw cycling).



**Figure 11.** Long-term strength of untreated loess and MICP-modified loess under cyclic freeze–thaw conditions [84]. (The arrows indicate the percentage reduction in long-term strength after freeze–thaw cycles compared with the initial value, and the dashed red lines indicate the initial long-term strength values of untreated loess and MICP-modified loess before freeze–thaw cycling).

Given that microbial communities can damage both the earthen fabric and associated heritage structures, it is necessary to conduct comprehensive analyses of microbial communities at archeological sites and to implement targeted preventive measures.

Biological deterioration poses a serious threat to the conservation of cultural heritage, and its impact on earthen sites in humid environments is particularly severe because their material properties make them highly vulnerable to attack. Microbial inhibitors can effectively mitigate biodeterioration of heritage sites by disrupting cellular metabolism, impairing physiological functions, and ultimately inducing cell death [85]. To address this challenge, Chang X et al. [86] developed a novel triple-action biocide, FACA, formulated by combining phenyl carbamothioyl thiazole compounds with isoquinolinone derivatives. FACA provides simultaneous antifungal, algicidal, and anti-lichen activity and exhibits strong inhibitory effects on key fungal species responsible for the deterioration of archeological sites. Moreover, FACA is a biodegradable compound that does not produce foam and therefore does not interfere with heat-transfer efficiency. The auxiliary biocidal and algicidal agents used in conjunction with this treatment also perform well, offering advantages such as being odorless, environmentally friendly, highly efficient, broadly applicable, cost-controllable, and practically convenient, thereby providing a reliable solution for the biological protection of earthen heritage sites.

#### 4.1.5. Anchoring and Grouting Reinforcement Methods for Earthen Heritage Sites

Cracking and small-scale erosional fissures in earthen heritage sites can markedly undermine their structural safety. To address cracking and fissure-related erosion, anchoring and fissure grouting can be employed as corresponding repair methods.

The core principle of anchoring technology is to transfer the tensile forces acting on the arch structure through the tensile capacity of the anchorage system, thereby greatly enhancing the structural stability of the earthen site. This type of support offers notable advantages such as high concealment and good construction quality, and in recent years it has been widely applied in the conservation of earthen heritage sites in humid environments. Under such special conditions, the anchor body must remain submerged in water for extended periods, which places stringent demands on the anchoring material in terms of deformability and durability. In dry environments, wood is commonly used as the anchoring material, whereas in humid environments, bamboo dowels, which exhibit superior durability, are generally preferred.

Gaofei S et al. [87] adopted micro-bamboo anchors as supporting elements in the conservation of the Tianluoshan earthen site in Ningbo. By varying the anchorage depth and the dry density of soil specimens, they found that within a certain depth range the anchoring force is positively correlated with dry density. In addition, Wang Y et al. [88], based on performance analyses of anchor bodies, pointed out that the anchor head is the component most prone to corrosion in actual use, and that such deterioration at the site is mainly induced by chloride ions rather than by groundwater or other factors. Current related research primarily focuses on the selection of anchoring materials, optimization of anchoring techniques, and the macroscopic anchorage performance and mechanisms of T-shaped anchoring systems. At the same time, studies on different types of anchor rods have continued to emerge, covering wooden anchors, bamboo anchors [89], bamboo-reinforced composite anchors [90], and glass fiber-reinforced polymer (GFRP) anchors [91], among others.

Anchored grouting technology integrates anchors, grout, and the in situ earthen body, mobilizing the collaborative action of the entire earthen body to achieve stable reinforcement of damaged areas. Grouting refers to the process by which specific materials are prepared into a slurry and then injected under pressure into the ground or into cracks using

specialized equipment, allowing the slurry to diffuse, gel, or harden so as to strengthen the ground or provide seepage control and leakage sealing [92]. Both methods require appropriate grout materials. Owing to its highly concealed nature, anchoring–grouting technology is being increasingly applied to the protection and reinforcement of geotechnical and architectural sites [68]. Traditional grouting materials are typically mixtures of lime powder, quartz sand, pozzolanic ash, and water, or mixtures of clay and limewater. At present, in the reinforcement of earthen heritage sites, grouting methods are mainly used to fill cracks within the soil mass. Because cracks in earthen sites located in dry environments are relatively prominent and the operational procedures are comparatively simple, this technique has achieved notable development under arid conditions [17].

Through systematic exploration and verification in practical applications, grouting reinforcement has become an effective method for the stabilization of cracks in earthen heritage sites. In the grouting process, the grout itself plays a pivotal role, and its properties have a pronounced influence on the reinforcement performance. At present, a variety of binders have been developed for this field, including polyvinyl alcohol (SH) [93], natural hydraulic lime (NHL) [94], and calcined ginger nuts (CGN) [95]. Lv J et al. [96] demonstrated that gypsum–quicklime–soil grout is a high-performance material for the restoration of earthen sites and can also be used for crack repair, achieving significantly better results than conventional crack-repair materials. In addition, Jiang et al. [97] incorporated basalt fibers (BF) into the grouting material to enhance the compressive and flexural strength of the grout, thereby improving the pull-out resistance of the anchorage system and strengthening the overall structural stability. These techniques show tremendous application potential in the reinforcement and conservation of earthen heritage sites.

#### *4.2. Technical Challenges and Preventive Measures Related to Coupled Environmental Factors*

Since 2006, with the implementation of a series of national research projects in the field of earthen-site conservation, China has gradually established a relatively complete theoretical foundation and technical protection system for the conservation of earthen heritage sites in arid environments. However, under the long-term combined influence of natural factors and human activities, these sites are facing progressive deterioration, manifested in such problems as collapse, erosion, cracking, weathering, encroachment by plant roots, waterlogging damage, and destruction caused by human activities, all of which pose serious threats to their long-term preservation and safe utilization. At present, most related studies focus on the independent action mechanisms of single environmental factors, whereas a systematic understanding of the deterioration mechanisms under multi-factor coupling remains notably insufficient [18].

The fundamental goal of conserving earthen heritage sites is to present to both present and future generations the rich values and meanings embodied in these precious cultural assets. However, in current practice there is a lack of coordination and alignment of objectives among the various stages of management, conservation, research, and utilization of such sites. It is therefore necessary, on the basis of the sites' outstanding universal value and in light of the current status and implementation of conservation techniques in different environmental settings (e.g., arid and humid regions), to systematically analyze and scientifically evaluate the impacts of environmental factors on site management, preventive conservation, and utilization. On this basis, application guidelines and specifications for management, prevention, intervention, and use should be formulated according to the environmental characteristics and conservation conditions of different regions, thereby establishing an integrated, collaborative conservation system that links value identification, technical implementation, and cultural transmission for earthen heritage sites. By giving equal emphasis to management strategies and conservation technologies, and by combin-

ing preventive conservation with maintenance and intervention measures, a long-term mechanism can be developed to ensure the sustained preservation and safe utilization of earthen heritage sites.

## 5. Comprehensive Conservation Measures

As shown in the previous chapter, deterioration mechanisms under single-factor conditions have been discussed in considerable depth. However, in real site environments salt migration and crystallization, wetting–drying cycles, freeze–thaw action, and wind erosion typically act simultaneously. Under such circumstances, it is difficult for any single measure or single indicator to consistently explain the evolution of damage, let alone provide a reliable basis for prediction. At the same time, in the absence of continuous on-site monitoring data, it is hard to validate experimental results and model outputs, which often cannot be directly matched to the actual behavior of the site; this, in turn, limits their usefulness for delineating high-risk zones and planning mitigation interventions. In light of these issues, the present chapter attempts to start from real field conditions and propose an integrated conservation approach, transforming existing research findings into more actionable protection strategies.

In complex environments where humidity, high salinity, and strong winds interact, earthen heritage sites are subjected to coupled deterioration driven by multiple factors, and traditional, localized single-protection measures are no longer sufficient to meet conservation needs. To effectively enhance the intrinsic resistance of the site fabric to environmental erosion, it has become imperative to develop comprehensive preventive conservation strategies that integrate multiple measures and ensure long-term effectiveness. Such strategies, grounded in macro-level approaches such as improving material properties, optimizing surface protection, and enhancing structural strength, aim to establish a more robust and durable protection system, thereby weakening environmental degradation processes at their source and promoting a shift in conservation practice from passive repair to proactive prevention. The following sections will discuss several representative comprehensive preventive conservation techniques and their prospects for application.

### 5.1. Physical Restoration Techniques

In the conservation of earthen heritage at historic sites, the adoption of efficient restoration measures is of critical importance. Common physical protection measures include installing protective shelters to reduce direct exposure to rainfall and intense solar radiation, as well as organizing surface drainage and controlling groundwater levels to lower the risk of water and salt accumulation caused by infiltration and capillary rise. For portions that are unsuitable for long-term exposure, backfilling with soil can be used to re-embed the remains in a more stable environment, where necessary in combination with windbreak and sand-fixation measures to mitigate aeolian abrasion and scouring. However, control at the levels of external environment and structural configuration alone is often insufficient to restore the bonding and water resistance of the near-surface earthen layer. Consequently, on-site interventions frequently need to be supplemented with material-based repair and reinforcement, improving the properties of the surface material to enhance durability. The following sections use several typical materials as examples to illustrate their roles and effectiveness in the restoration of earthen heritage sites.

Glutinous rice paste has emerged as an ideal option owing to its outstanding overall performance, including high bonding strength, good toughness, moisture and water resistance, durability under hot and humid conditions, and excellent anti-aging properties, making it particularly suitable for applications requiring strong structural adhesion. Pei et al. [98] innovatively proposed and evaluated a restoration and reinforcement technique

based on in situ modification of site earthen material with glutinous rice paste, whereby the paste was incorporated into site earthen materials using different procedures to produce glutinous-rice-modified earthen materials for damaged earthen sites. Experimental results showed that soil modified with gelatinized glutinous rice slurry exhibited the best water resistance. After being subjected to 50 freeze–thaw cycles, alternating temperature–humidity cycles, and four  $\text{Na}_2\text{SO}_4$  salt-corrosion cycles, this modified earthen material retained a significantly higher proportion of its strength than the other groups. Detailed analysis revealed that gelatinized glutinous rice paste enhances the structural compactness of the site earthen material, thereby not only effectively increasing its strength but also markedly suppressing its disintegration in aqueous environments, thus providing a long-term conservation solution for earthen heritage sites that integrates traditional wisdom with modern technology.

Tung oil possesses excellent waterproofing properties, dries rapidly, and readily oxidizes to form a film, whereas glutinous rice slurry is characterized by high viscosity, strong toughness, and low expansibility. Numerous historical records document that tung oil and glutinous rice slurry were commonly used in ancient China for the construction of city walls and palace fortifications, and many such structures exhibit high strength and long-term durability, indicating that these materials and techniques have considerable research and application value. Tang X. W et al. [99] investigated silt soils modified with glutinous rice slurry and tung oil, examining the effects of these additives on the strength and permeability of the composite material, and determined an optimal mass ratio of tung oil, glutinous rice slurry, and soil of 5:10:85. In this system, the viscosity of the glutinous rice slurry bonds soil particles together, while the rapid drying of tung oil leads to the formation of a dense oxidized film that further immobilizes the bonded particles. When the two additives act synergistically at the optimal mass ratio, a dual-film structure is formed, which not only markedly reduces the permeability of the material but also enhances its shear strength. After treatment with the optimal mix proportion, changes at the treated material surface are minimal and barely distinguishable to the naked eye, a feature that is well suited to the requirements of earthen heritage conservation.

Calcined plant ash (CGN) has shown considerable application potential in the restoration and stabilization of earthen heritage sites, and extensive studies have successfully introduced it into conservation practice. Peng E et al. [95] demonstrated that CGN-stabilized earthen material can be used for compaction in eroded zones of earthen sites: it not only improves the weathering resistance of the earthen material, but also exhibits good compatibility with the in situ earthen material within a certain dosage range, with only minor color differences, making it a highly promising reinforcing material for eroded areas. As the CGN content and curing time increase, the properties of the stabilized specimens change as follows: shear strength and unconfined compressive strength show modest increases; the permeability coefficient decreases slightly; the disintegration rate (Table 2) and shrinkage rate (Table 3) are markedly reduced; at the same time, the total color difference in the specimens increases with increasing brightness. Moreover, CGN significantly enhances the weathering resistance of the specimens, providing multiple lines of evidence for its feasibility as a stabilizing and consolidating agent for earthen heritage sites.

**Table 2.** Disintegration rate of soil samples [95].

| Curing Time (d) | Dosage (%) | 5      | 10     | 15     | 20 | 25 | 30 | 35 |
|-----------------|------------|--------|--------|--------|----|----|----|----|
| 3               | 100%       | 80.85% | 46.81% | 17.78% | 0% | 0% | 0% | 0% |
| 7               | 100%       | 73.33% | 11.11% | 0%     | 0% | 0% | 0% | 0% |
| 14              | 100%       | 66.66% | 0%     | 0%     | 0% | 0% | 0% | 0% |
| 28              | 100%       | 60.42% | 0%     | 0%     | 0% | 0% | 0% | 0% |
| 60              | 100%       | 55.56% | 0%     | 0%     | 0% | 0% | 0% | 0% |

**Table 3.** Stable linear shrinkage values of CGN-stabilized soil specimens with different CGN dosages [95].

| Dosage (%)                 | 0    | 5    | 10   | 15   | 20   | 25   | 30   | 35   |
|----------------------------|------|------|------|------|------|------|------|------|
| Stable shrinkage value (%) | 0.57 | 0.45 | 0.43 | 0.33 | 0.32 | 0.31 | 0.29 | 0.23 |

### 5.2. Chemical Restoration Techniques

Because the constituent materials of earthen heritage sites possess inherently low mechanical strength, such sites face severe challenges in humid environments. Moisture infiltration, freeze–thaw cycling, and biological attack continuously damage the site fabric. Consequently, for the protection of earthen sites under humid conditions, the application of hydrophobic sealing materials has become a key strategy. Owing to their unique properties, superhydrophobic coatings show remarkable potential in the protection of earthen heritage, and their core characteristics—water repellency, vapor permeability, mechanical strength, and optical transparency—offer new directions for conservation practice. Liu Y et al. [19] reported that superhydrophobic materials exhibit excellent performance in terms of corrosion resistance, self-cleaning, anti-freezing, and anti-scaling, effectively blocking water ingress, reducing the risk of water-related damage to earthen sites, and providing technical support for the long-term preservation of cultural heritage. In particular, superhydrophobic coatings with self-cleaning capability are regarded as an important future development direction for earthen-site conservation. However, several urgent issues remain in practical applications: the deterioration mechanisms of earthen sites and the working mechanisms of existing protective coatings are not yet fully understood; the durability of such coatings under extreme environmental conditions is still inadequate; and there is a lack of unified quality evaluation standards. These limitations currently constrain the widespread application of superhydrophobic coatings in the conservation of earthen heritage sites [100].

In the conservation of earthen heritage sites, the selection of suitable materials has long been a key challenge. Although organic materials generally exhibit good penetrability, their poor compatibility with the original fabric and limited resistance to aging make it difficult for them to meet practical application requirements. Inorganic materials, by contrast, tend to have longer service lives and better compatibility, but their limited capacity for strength enhancement and relatively poor penetrability constrain their large-scale use [101]. Past conservation practice has clearly shown that no single material can provide comprehensive and effective protection for earthen sites. Against this background, novel composite materials combining organic and inorganic components have emerged as a new direction in the reinforcement of earthen heritage [102]. Chen W et al. [59] systematically compared the protective performance of single materials and composite materials in order to explore the application potential of composites in earthen-site conservation, and conducted multi-dimensional evaluations of changes in color, weight, mechanical properties, water resistance, microstructure, and elemental composition of the treated earthen materials. The results indicate that appropriately designed reinforcement sequences using composite ma-

terials can markedly optimize material properties. When organic and inorganic materials are each used at half their original dosages to form a composite, substantial improvements are achieved in surface hardness, longitudinal wave velocity, unconfined compressive strength, and water resistance. Thus, composite materials hold great promise in the field of cultural heritage conservation and are expected to become an important technical support for the future protection of earthen heritage sites.

In recent years, modified earthen materials have been widely used as repair materials in collapse-remediation projects for earthen heritage sites. Because most earthen sites are exposed to open environments, their exposed earthen materials are readily subjected to attack by acid rain and acidic components in groundwater [103]. Although natural hydraulic lime (NHL)-modified earthen material exhibits good mechanical performance, its durability is inadequate when used as a repair material for earthen sites. Ma Q et al. [104] sought to enhance the durability and prolong the service life of this NHL-modified earthen repair material by adding sodium methyl silicate. The incorporation of sodium methyl silicate increases the compressive strength of hydraulic-lime-modified earthen materials and reduces their saturated water absorption; although it leads to some reduction in shear strength, it significantly improves the resistance of the material to wetting-drying cycles. In addition, this additive forms a hydrophobic layer on the surfaces of the modified earthen particles, further enhancing their erosion resistance and water resistance. The study showed that when the sodium methyl silicate content is 0.3%, NHL-modified earthen material can achieve both excellent mechanical properties and durability, which was identified as the optimal mix proportion.

### *5.3. Limitations of Existing Measures and Directions for Improvement*

The physical and chemical restoration techniques reviewed in this chapter can all mitigate, to some extent, the deterioration of earthen heritage sites, but each has clear limitations. Overall, the problem does not lie in any single method being ineffective; rather, it lies in the fact that on-site deterioration is typically driven by multiple factors acting in concert, so that no single intervention can reliably and sustainably cover all risks over the long term.

The main limitation of physical restoration techniques is that their effectiveness depends heavily on site-specific conditions and long-term maintenance. They are often effective only for a particular type of problem and may simultaneously introduce new deterioration risks in other respects. For example, without the support of continuous monitoring, it is difficult to detect micro-environmental shifts in time when measures such as shelters and enclosures, drainage and water diversion, or ventilation and humidity control are implemented; as a result, their actual performance may fluctuate with the seasons and the quality of site management, and may even cause local moisture accumulation, thereby exacerbating risks of salt damage or biologically induced deterioration. Thus, physical interventions are closer to ongoing management than to one-off treatments, and must be combined with monitoring to ensure their effectiveness. The shortcomings of chemical restoration techniques, by contrast, are mainly associated with uncertainties in compatibility and durability. Although consolidants or surface treatments can often enhance strength in the short term, they may alter the pore structure and the pathways of water-vapor transport, shifting the locations of salt crystallization; under long-term salt attack and fluctuating temperature-humidity conditions, their effectiveness is prone to decay, and issues such as color change and alteration of surface appearance may arise. Recent studies therefore emphasize the need for multi-parameter evaluation methods to assess the true impact of chemical treatments on the near-surface layers of the earthen fabric.

In summary, both physical and chemical approaches have their value, but each has clear boundaries of applicability. A more appropriate direction for future work is to combine different measures into integrated intervention packages, to use monitoring data to verify their performance, and to adjust them in a timely manner based on the results, so that short-term effects can be transformed into long-term conservation outcomes.

#### *5.4. Emergency Stabilization Measures for Ongoing Degradation*

In addition to long-term preventive conservation, emergency stabilization measures are necessary for earthen heritage sites that are undergoing active deterioration or facing immediate risks such as partial collapse, severe erosion, water infiltration, or rapid surface loss. Such measures are temporary interventions intended to reduce immediate risk and provide time for detailed investigation and long-term conservation planning.

For sites in emergency condition, rapid documentation and risk assessment should be carried out first to identify unstable zones and the main pathways of ongoing deterioration. Depending on the urgency and damage type, temporary actions may include provisional sheltering, waterproof covering, drainage and runoff diversion, local support or bracing, protective covering, backfilling, and, where necessary, emergency grouting or temporary anchoring under professional supervision. These interventions should be compatible with the original earthen fabric and should remain as reversible and minimally invasive as possible.

Emergency stabilization should be accompanied by short-term monitoring of cracks, moisture variation, deformation, and surface loss. After the immediate risk is controlled, temporary interventions should be incorporated into a longer-term conservation strategy based on site-specific deterioration mechanisms, environmental conditions, construction techniques, and material compatibility.

## **6. Discussion and Conclusions**

This paper has reviewed the core mechanisms of deterioration in earthen heritage sites, outlined the effects of both single-factor and multi-factor coupling, and summarized recent advances in targeted conservation techniques and their applications. The main factors governing the stability of earthen sites include salt-induced erosion, wetting–drying cycles, wind erosion, microbial activity, freeze–thaw cycles, and multifactor coupling effects, among which surface powdering and internal crystallization pressure caused by salt attack, as well as pore expansion and loss of structural strength induced by the coupling of freeze–thaw action and salinization, are particularly prominent. On this basis, existing studies, particularly those focusing on Chinese earthen heritage sites, have proposed conservation strategies that combine targeted protection against individual deterioration factors with coordinated protection under multiple interacting factors. Representative measures include PVA hydrophobic sublayers and sand-layer barriers for salt-damage control, PS solution treatments and SAP water-retaining resins for wind-erosion protection, MICP bio-reinforcement and the broad-spectrum biocide FACA for microbiologically induced pathologies, and physico-chemical restoration techniques such as glutinous-rice-modified earthen materials and superhydrophobic coatings for comprehensive preventive conservation, alongside structural reinforcement methods including anchorage support and fissure grouting. Overall, these comprehensive preventive approaches—by enhancing hydrophobicity, improving mechanical properties, optimizing microstructure, or forming protective film layers—strengthen the capacity of earthen sites to resist salt ingress, moisture fluctuations, wind erosion, and freeze–thaw damage, and are generally superior to localized repairs in terms of systemic perspective and long-term foresight. At the same time, surface weathering and structural instability remain key challenges for reinforcement and

conservation. Taking rammed-earth sites in arid regions as an example, a technical system has been developed that encompasses anchor-rod anchorage and fissure grouting, together with specialized materials such as bamboo composite anchors, PS-F grouts, and PS-based chemical consolidants; nevertheless, the applicability of this system is still constrained by variations in construction techniques and environmental conditions across different sites. In engineering practice, additional challenges persist, including the insufficient long-term stability of materials under extreme climatic conditions, the need to balance cost and benefit for large-scale application, incomplete standardization of construction procedures, and the requirement to preserve the authenticity of the sites. In addition, the applicability of deterioration mechanisms and conservation measures should be interpreted in relation to different earthen construction techniques. Although salt migration, wetting–drying cycles, wind erosion, microbial activity, and freeze–thaw action are common risk factors for earthen heritage, their manifestations and the effectiveness of conservation treatments may vary among rammed earth, adobe or earthen-block masonry, wattle and daub, and other mixed earthen systems. In the literature reviewed here, rammed-earth walls and exposed earthen-wall remains provide the strongest experimental basis, whereas the transferability of these findings to adobe and wattle-and-daub structures still requires further validation because of differences in compaction state, block or joint interfaces, organic reinforcement, pore structure, and moisture-transport pathways. Therefore, the conservation techniques summarized below should be understood as construction-technique-dependent rather than universally applicable to all earthen architectural forms.

The applicability of deterioration mechanisms and conservation measures should be interpreted in relation to regional climate, material characteristics, and construction techniques. Although salt migration, wetting–drying cycles, wind erosion, microbial deterioration, and freeze–thaw action are common risk factors for earthen heritage sites, their relative importance and damage patterns vary among different regions of China. For example, earthen sites in arid and semi-arid regions are more likely to suffer from salt crystallization, wind erosion, and moisture accumulation at wall bases, whereas sites in cold regions are more sensitive to freeze–thaw-related cracking and strength loss. In humid or seasonally wet regions, rainfall erosion, wetting–drying cycles, and biological deterioration may become more prominent. Meanwhile, the effectiveness of conservation treatments may differ among rammed earth, adobe or earthen-block masonry, cob, earthen renders or plasters, wattle and daub, and other mixed earthen systems because of differences in material composition, compaction state, pore structure, joints, organic additives, and moisture-transport pathways. Therefore, the conservation techniques summarized below should be understood as region-, material-, and construction-technique-dependent rather than universally applicable to all Chinese earthen heritage sites.

Consistent with the classification used in Section 3, the major deterioration mechanisms are summarized here as salt-induced erosion, wetting–drying cycles, wind erosion, microbial deterioration, freeze–thaw cycles, and multifield coupling. Rather than presenting conservation techniques as isolated measures, the following synthesis explicitly links the deterioration problems identified in Section 3 with the corresponding conservation objectives and technical responses, and compares them according to the mechanisms they target, the type of evidence supporting their effectiveness, their applicability to different site conditions and earthen construction forms, and their main limitations in terms of durability, compatibility, and practical implementation. To make the mechanism–intervention relationship clearer, Table 4 is organized as an analytical mapping table. It links each major deterioration issue with its associated damage forms, causal mechanisms, climatic or regional context, relevant material and construction conditions, corresponding conservation strategies, evidence basis, suitability, and main limitations.

As shown in Table 4, different conservation techniques have distinct advantages and limitations. Measures such as superhydrophobic coatings, glutinous-rice-paste- and tung-oil-based composite materials, calcined plant ash, siliceous consolidants, sodium-methyl-silicate-modified repair materials, anchoring, and grouting can address specific deterioration problems to varying degrees. However, under long-term exposure to coupled environmental stressors, such as moisture migration, salt crystallization, wind erosion, freeze–thaw action, microbial deterioration, and structural instability, no single material or single intervention can fully satisfy all requirements for water resistance, salt resistance, wind-erosion resistance, material compatibility, and structural safety. Therefore, effective conservation should shift from the sequential application of individual techniques to integrated protection strategies that combine material modification, surface protection, drainage control, structural reinforcement, monitoring, and site-specific maintenance. Nevertheless, these integrated strategies still require further validation in terms of long-term stability, compatibility with different earthen construction techniques, and the standardization of construction procedures.

Taken as a whole, the deterioration of earthen heritage sites is dominated by the superposition and coupling of multiple factors. Although single-factor mechanistic studies have laid a foundation for understanding damage processes, reliance on a single indicator or isolated measure cannot provide a stable explanation or prediction of long-term evolution, nor can it ensure robust performance under complex boundary conditions. Building on a systematic review of existing work, this paper further points out that the main weaknesses of current research lie in the gap between laboratory conditions and the actual environments of heritage sites. In particular, mixed-salt and multi-ion conditions, diurnal temperature–humidity fluctuations, and multifield coupling processes can all alter water–salt migration and damage pathways, while the lack of continuous monitoring undermines the validation of experimental and modeling results, making it difficult for research conclusions to reliably support on-site decision-making. At the level of conservation strategies, this paper also supplements and emphasizes the necessity of holistic preventive protection and multi-technology synergy, thereby making the set of options and combination approaches beyond purely physical and chemical methods more complete and better aligned with the practical needs of long-term preventive conservation. Future research can be advanced in three directions. First, long-term continuous monitoring systems should be established under real site-specific environmental conditions, using continuous data to link temperature–humidity variations, water–salt migration, and damage development, and then employing these data to validate experimental findings and model outputs. Second, more field-like validation studies should be carried out under scenarios of combined action by multiple factors, focusing on assessing the durability and applicability ranges of different materials and measures under combined salt damage, wetting–drying, freeze–thaw, and wind-erosion conditions, and elucidating failure processes under extreme climates. Third, under the premise of preserving the authenticity of the sites as far as possible, research should explore environmentally friendly and functionally integrated protective materials and technologies, with the aim of developing comprehensive conservation schemes capable of long-term operation.

**Table 4.** Analytical mapping between deterioration issues, damage forms, causal mechanisms, applicable contexts, conservation strategies, evidence basis, suitability, and limitations.

| Deterioration Issue     | Associated Damage Forms                                                                                                   | Main Causal Mechanisms                                                                                                                              | Climatic or Regional Context                                                                          | Relevant Construction or Material Conditions                                                                                       | Corresponding Conservation Strategies                                                                                                             | Evidence Basis and Suitability                                                                                                                                      | Main Limitations                                                                                                                                                              |
|-------------------------|---------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Salt-induced erosion    | Salt efflorescence, surface powdering, crust spalling, basal weakening, local material loss                               | Capillary rise, soluble-salt migration, evaporation-driven salt accumulation, crystallization pressure, repeated dissolution–crystallization cycles | Arid and semi-arid regions; sites with strong evaporation, groundwater influence, or salt-rich soils  | Exposed earthen walls with high porosity, weak surface layers, soluble salts, or moisture-transport pathways at wall bases         | Drainage improvement, moisture control, salt-migration inhibition, compatible surface protection, hydrophobic treatment where appropriate         | Mainly supported by laboratory salt-cycling tests, material tests, and site observations; suitable where salt migration and moisture supply can be reduced together | Salt sources are difficult to remove completely; inappropriate waterproofing may trap moisture and salts inside the earthen fabric; long-term performance requires monitoring |
| Wetting–drying cycles   | Shrinkage cracking, surface peeling, strength loss, repeated expansion–contraction damage                                 | Alternating water absorption and evaporation, swelling–shrinkage of clay minerals, pore-structure change, progressive loss of cohesion              | Humid or seasonally wet regions; sites affected by rainfall, runoff, or repeated moisture fluctuation | Clay-rich earthen materials, exposed surfaces, earthen renders or repair layers, and interfaces sensitive to moisture variation    | Hydrophobic treatment, compatible repair materials, material modification, surface protection, rainfall and runoff control                        | Supported by wetting–drying cycle tests and durability evaluation of modified materials; suitable for sites with repeated moisture fluctuation                      | Some treatments may reduce vapor permeability or alter surface appearance; durability under long-term cyclic exposure needs further validation                                |
| Wind erosion            | Surface abrasion, particle loss, edge erosion, wall-top erosion, local undercutting when combined with moisture and salts | Wind-blown sand impact, airflow acceleration at edges and openings, removal of loosened particles, coupling with moisture and salt weakening        | Arid and semi-arid regions; open sites exposed to strong wind and sand movement                       | Exposed rammed-earth walls, wall tops, corners, openings, and surfaces with weak cohesion or insufficient surface protection       | Surface consolidation, anti-weathering protection, sacrificial covering, protective sheltering, windbreak or vegetation control where appropriate | Supported by wind-erosion tests, material-loss evaluation, and field observations; suitable for exposed sites where wind abrasion is a dominant factor              | Consolidants may have limited penetration depth; excessive stiffness or poor compatibility may cause secondary damage; shelters may alter microclimate                        |
| Microbial deterioration | Biological colonization, discoloration, surface weakening, biofilm formation, local material alteration                   | Moisture retention, microbial growth, metabolic activity, biogenic mineral or organic deposits, interaction with surface salts and nutrients        | Humid or seasonally wet regions; shaded or poorly ventilated areas with sufficient moisture           | Earthen surfaces with persistent moisture, organic additives, surface deposits, or rough pore structures that support colonization | Moisture control, environmental regulation, reversible cleaning, biological inhibition, compatible preventive treatment                           | Supported by microbial identification, laboratory inhibition tests, and site cleaning or treatment experience; suitable where biological growth is moisture-driven  | Recolonization may occur if moisture is not controlled; biocidal treatments may raise ecological or material-compatibility concerns                                           |

Table 4. Cont.

| Deterioration Issue | Associated Damage Forms                                                                                    | Main Causal Mechanisms                                                                                                                                           | Climatic or Regional Context                                                                          | Relevant Construction or Material Conditions                                                                                      | Corresponding Conservation Strategies                                                                                                                           | Evidence Basis and Suitability                                                                                                                            | Main Limitations                                                                                                                                                                    |
|---------------------|------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Freeze–thaw cycles  | Cracking, granular disintegration, surface scaling, strength loss, structural loosening                    | Freezing and expansion of pore water, ice-lens formation, repeated freeze–thaw stress, microcrack propagation                                                    | Cold regions or areas with frequent temperature fluctuation around 0 °C and sufficient pore water     | Earthen materials with high water content, vulnerable pore structures, cracks, or insufficient drainage                           | Moisture reduction, drainage improvement, protective sheltering, compatible consolidation, crack filling where necessary                                        | Supported by freeze–thaw cycle tests and cold-region site observations; suitable when water ingress can be reduced before freezing                        | Ineffective if water supply continues; performance depends strongly on pore structure and moisture content; long-term field validation is needed                                    |
| Multifield coupling | Combined cracking, salt-related spalling, basal erosion, surface loss, deformation, structural instability | Interaction among moisture migration, salt crystallization, wind erosion, freeze–thaw action, microbial deterioration, structural defects, and human disturbance | Sites exposed to multiple stressors, especially arid–cold, arid–windy, or seasonally wet environments | Complex earthen structures with heterogeneous materials, previous repairs, cracks, weak interfaces, or structural discontinuities | Integrated strategies combining monitoring, drainage, surface protection, material modification, anchoring, grouting, sheltering, and site-specific maintenance | Supported by combined laboratory tests, field monitoring, and conservation case studies; suitable for sites where single-factor treatment is insufficient | Coupled mechanisms are difficult to reproduce fully in laboratory tests; interventions require site-specific design, long-term monitoring, and standardized construction procedures |

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