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Research Article

ENHANCING TEPETATE RENDERS WITH ENDEMIC PLANT MUCILAGE AND SAFE ADDITIVES: A SUSTAINABLE APPROACH TO ARCHITECTURAL CONSERVATION

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Abstract

This study investigates the transformation of tepetate renders through the addition of heteropolysaccharides and industrial byproducts for use in architectural restoration, with a focus on sustainable and eco-friendly practices. Tepetate, a volcanic soil common in Mexico, has limitations as a plaster material due to its poor cohesiveness and durability. We hypothesized that the addition of mucilage from endemic plants (*Opuntia aciculata, Agave lechuguilla,* and *Cyrtopodium macrobulbon*) and industrial byproducts (glycerol) could improve tepetate properties for restoration applications while promoting ecological conservation and resource efficiency. We conducted experiments using various concentrations (0.5%, 1%, and 1.5%) of these additives and subjected samples to cohesiveness, aging, compression strength, and water absorption tests. Results showed significant improvements in tepetate properties, with some variations depending on the additive type and concentration. Notably, agave mucilage at 0.5% concentration achieved the highest compressive strength (42.09 kg/cm^2), while glycerol at 1.5% demonstrated superior water resistance. All additive mixtures reduced water requirements by at least 40% compared to the control sample, with some achieving up to 62.5 % reduction. This water-saving aspect, combined with the use of natural and waste materials, underscores the ecological benefits of the proposed approach. The addition of these natural and industrial additives can effectively enhance tepetate performance as a rendering material, offering a sustainable solution for architectural conservation. These findings contribute to the development of improved, environmentally friendly materials for the restoration of cultural heritage buildings, aligning with principles of resource conservation and circular economy practices in the field of restoration.

Keywords: Tepetate renders, heteropolysaccharides, sustainable restoration, endemic plants, construction materials

1. INTRODUCTION

The preservation of cultural heritage buildings is a critical aspect of maintaining historical and cultural identity. Cultural heritage represents a crucial socioeconomic resource that embodies past human legacy while depicting present and future ways of life, enhancing solidarity and social integration of communities. In Mexico, a country rich in architectural heritage, the restoration of immovable cultural properties presents unique challenges and opportunities. These structures, ranging from pre-Hispanic constructions to colonial-era buildings, reflect a diverse array of architectural influences and styles. However, the passage of time, environmental factors, and human interventions have left their mark on these structures, necessitating careful and sustainable approaches to restoration. Plasters and mortars play a crucial role in the preservation of immovable heritage and must be taken into great consideration when conserving historical buildings.

Plasters play a crucial role in the protection and preservation of historical buildings. Traditionally, renders have served not only as aesthetic finishes but also as sacrificial layers that shield the underlying structure from environmental degradation. In the context of restoration, the choice of rendering materials is paramount, as they must be compatible with the original structure while providing adequate protection against moisture, erosion, and other forms of decay.

Conservation can be required where decay or failure threatens survival and often entails preservation, repair and frequently reinstatement within the context of existing historic fabric. The significance of these materials in conservation extends beyond their functional properties to encompass their role in maintaining architectural authenticity, providing protective barriers against environmental degradation, and ensuring structural stability of heritage buildings. They are particularly applicable in cases involving protective coatings for facades exposed to harsh climates, restoration of decorative elements that require compatible materials with similar thermal expansion properties, and consolidation of deteriorated surfaces where modern materials might cause incompatibility issues with historical substrates.

Tepetate, a volcanic soil widely available in Mexico, was used in construction for centuries. Its abundance and low cost make it an attractive option for restoration projects. However, tepetate in its natural state presents limitations when used as a plastering material. Its cohesiveness, adherence, and durability are often insufficient for effective surface protection, particularly when transformed into construction components (Armendáriz Márquez, 2012; Guerrero Baca, 2020).

Recent research has shown promise in the use of natural additives, particularly mucilage from endemic plants, to improve the properties of earthen construction materials (García-Alonso et al., 2022; Guerrero Baca., 2019). These studies have primarily focused on the use of *Opuntia ficus-indica* (prickly pear cactus or “nopal” in spanish) mucilage, demonstrating improvements in physical properties of various earth-based materials, including tepetate.

The exploration and utilization of native plants in this context carry significant cultural and ecological importance. Indigenous communities in Mexico have long recognized the beneficial properties of local flora, incorporating them into traditional building practices. By experimenting with and validating these traditional knowledge systems, we not only preserve cultural heritage but also promote biodiversity conservation and sustainable resource management. The selection of *Opuntia aciculata*, *Agave lechuguilla*, and *Cyrtopodium macrobulbon* was based on several strategic considerations:

- *Opuntia aciculata* was chosen as an endemic variation of the well-studied *Opuntia ficus-indica* (Santos, 2023), offering potential for localized applications with similar mucilaginous properties but adapted to specific regional conditions.
- *Agave lechuguilla* represents an underexplored resource with significant potential, as agave fibers have demonstrated remarkable improvements in construction materials, with studies showing up to 99% increase in flexural resistance and 86% improvement in compressive resistance in lime-based concretes, while also offering excellent compatibility with non-cement matrices. Agave leaves contain high amounts of fiber (38.40%), total sugars (45.83%), and proteins (35.33%), indicating rich mucilaginous compounds suitable for construction applications (Mahmood, 2024).
- *Cyrtopodium macrobulbon*, a terrestrial orchid, represents an innovative choice based on its complex chemical composition. This species contains complex sugar mucilage, suggesting potential beneficial properties for construction applications through their chemical stability and phisical characteristics (García-Alonso & Ruvalcaba, 2020).

The use of these endemic species, particularly the inclusion of an orchid mucilage, represents a bridge between ancestral wisdom and modern scientific inquiry, potentially leading to innovative, locally sourced solutions for architectural conservation while contributing to the preservation of botanical knowledge.

Recently, there is growing interest in the utilization of industrial byproducts in construction and restoration practices, aligning with principles of circular economy and sustainable resource management. Byproducts such as glycerol from biodiesel production represent potential resources that, if properly harnessed, could contribute to more sustainable restoration practices.

This study aims to expand on previous research by investigating the potential of multiple heteropolysaccharides and industrial byproducts in improving the properties of tepetate for use in restoration renders. Specifically, we explore the effects of mucilage extracted from *Opuntia aciculata, Agave lechuguilla,* and *Cyrtopodium macrobulbon*, as glycerol, on the physical and mechanical properties of tepetate renders.

The primary objectives of this research are:

1. To evaluate the effects of different heteropolysaccharides and industrial byproducts on the cohesiveness, adherence, water resistance, and durability of tepetate renders.

2. To determine optimal concentrations of these additives for improving tepetate properties while minimizing water usage.

3. To assess the potential of these modified tepetate renders for use in the restoration of immovable cultural properties.

By exploring these novel combinations of natural and industrial additives, this study seeks to contribute to the development of more effective, sustainable, and environmentally friendly materials for architectural conservation. The findings of this research have the potential to not only improve restoration practices but also to promote the use of locally available resources and industrial byproducts, thereby supporting ecological conservation efforts in the field of cultural heritage preservation.

2. MATERIALS AND METHODS

1. Materials

1.1 Tepetate

We selected tepetate from the Tlaxco region as the base material for this study. The tepetate came in compact clods and we had to disaggregate it for laboratory use. According to data from the "Geotecnia aplicada a la ingeniería civil S.A. de C.V." laboratory, the tepetate contained 20.1% sand and 79.9% fines, with a Liquid Limit of 27.5, Plastic Limit of 19.24, and Plasticity Index of 8.26. It was classified as a "CL" soil type (inorganic clayey soil of low plasticity) according to the Unified Soil Classification System (USCS).

1.2 Heteropolysaccharides

We extracted three types of mucilage from endemic plants:

1. *Opuntia aciculata* (nopal): Obtained from the Laboratory of Traditional Technologies (Tectrad).
2. *Agave lechuguilla*: Sourced from Catarinas Minas, Oaxaca region.
3. *Cyrtopodium macrobulbon*: Obtained from the central market area of Oaxaca.

Figure 1. 1. *Opuntia aciculata*, 2. *Agave lechuguilla* and 3. *Cyrtopodium macrobulbon* flower

1.3 Industrial Byproducts

We used the following industrial byproducts:

1. Glycerol: USP grade glycerin supplied by the Tectrad laboratory.

2. Methods

2.1 Extraction of Heteropolysaccharides

1. *Opuntia aciculata*
   We cut the prickly pear cactus in half, and carefully extracted the mucilage using a rounded wooden tool, yielding approximately 70 ml of mucilage with a pH measured at 5.78.
2. *Agave lechuguilla*
   We cut and macerated a 25 cm (150 g) section of the leaf and added 175 ml of distilled water. After filtration, we obtained 280 ml of mucilage with a pH of 4.52.
3. *Cyrtopodium macrobulbon*

We halved and macerated two bulbs and added 175 ml of distilled water was to 150 g of fibrous material. After filtration, we obtained 200 ml of mucilage with a pH of 5.60.

2.2 Characterization of Glycerol

We used USP grade glycerin known for its high viscosity and hygroscopic properties. We measured its pH at 6.14.

2.3 Preparation of Tepetate Samples

We sieved the tepetate through a No. 10 mesh (2 mm aperture). For each cubic sample, we used 200 g of sieved tepetate. The liquid content varied (water, mucilage, or industrial byproducts) to achieve proper consistency for rendering.

2.4 Testing Procedures

2.4.1 Cohesiveness Test

We formed bars of 1.5 cm diameter and 20 cm length and allowed them to hang over the edge of a table until they broke then we measured the length of the broken sections to determine cohesiveness.

2.4.2 Aging Test

We subjected the samples to an aging chamber for 93 days (July 25 to October 25, 2023). The chamber simulated varying conditions of temperature, humidity, and UV/IR radiation designed to replicate Mexican open-air conditions. Accelerated weathering chambers reproduce the damaging effects of materials by simulating sunlight, moisture, and temperature cycles, where a few days or weeks of UV exposure can reproduce the damage that occurs over months or years outdoors (Pickett, 2005).

2.4.3 Compression Strength Test

Cubic samples (5 cm x 5 cm x 5 cm) were tested after 28 days of curing using a Dillon Weigh Tronix Inc machine with a Dillon FI-90 indicator.

2.4.4 Absorption Tests

We conducted three absorption tests:

1. Italian Test: We weighed and submerged the samples in water for 30 seconds, and then reweighed them. This process was repeated for 15 minutes or until the sample began to disintegrate.
2. Karsten Tube Test: We applied a 4 ml volume of water to the sample surface using a Karsten tube. Absorption was monitored for the first 5 minutes and then until complete absorption.
3. Total Immersion Test: We completely submerged the samples in water, and recorded the time until complete disintegration.

We conducted tests using tepetate samples with varying concentrations (0.5%, 1%, and 1.5%) of the mucilage and industrial byproduct. Control samples using only tepetate and water were also prepared and tested for comparison.

3. RESULTS AND DISCUSSION

3.1 Water Reduction in Mixtures

All mixtures with additives showed a significant reduction in water requirement compared to the control sample. The most notable reductions were orchid mucilage at 0.5% and fresh nopal mucilage at 1% achieving 62.5% water reduction, and agave mucilage at 1.5% achieving 65% water reduction.

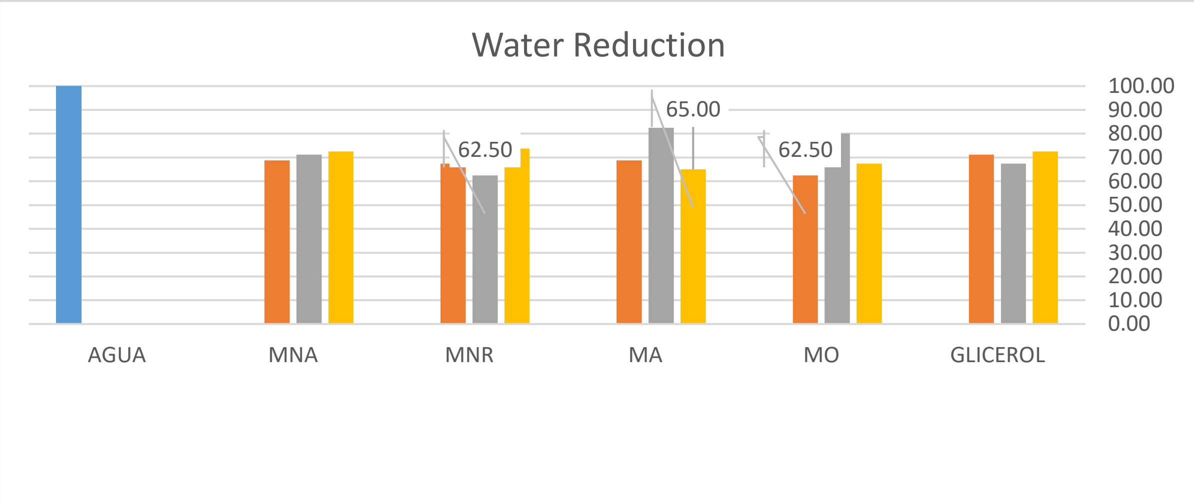

Figure 2. Blue bar represents water usage without any additives, orange bar represents 0.5 additive concentration, grey bar 1.0 and yellow bar 1.5 percentage. With all additives the reduction of water consumption was significant especially with orchid mucilage (MO) and Agave mucilage (MNR).

3.2 Cohesiveness Test

Optimal cohesiveness for base renders (6-9 cm fragments) was achieved by:

- Aged nopal mucilage at 1% and 1.5%
- Fresh nopal mucilage at all concentrations (0.5%, 1%, 1.5%)
- Agave mucilage at 1% and 1.5%
- Orchid mucilage at 1%
- Glycerol at 1%

3.3 Aging Test

After 93 days in the aging chamber:

- No significant changes were observed in samples exposed to normal environmental conditions.
- Samples in the aging chamber showed a notable reduction in the render layer thickness but maintained structural integrity without significant detachment.

3.4 Compression Strength Test

The control sample (tepetate with water only) showed a compressive strength of 16.36 kg/cm². All samples with additives surpassed this value. The highest compressive strengths were:

1. Agave mucilage at 0.5%: 42.09 kg/cm²
2. Orchid mucilage at 1.5%: 39.73 kg/cm²

Notably, aged nopal mucilage and glycerol showed consistent strength across all concentrations (25-27 kg/cm² and 33-35 kg/cm² respectively).

3.5 Water Absorption Tests

3.5.1 Karsten Tube Test

- Control sample absorbed 0.81 ml in the first 5 minutes.
- Samples with 1.5% concentration generally showed lower water absorption.
- Orchid mucilage at 1.5% took the longest to absorb 4 ml (471 minutes), followed by glycerol at 1.5% (422 minutes) and aged nopal mucilage at 1.5% (346 minutes).

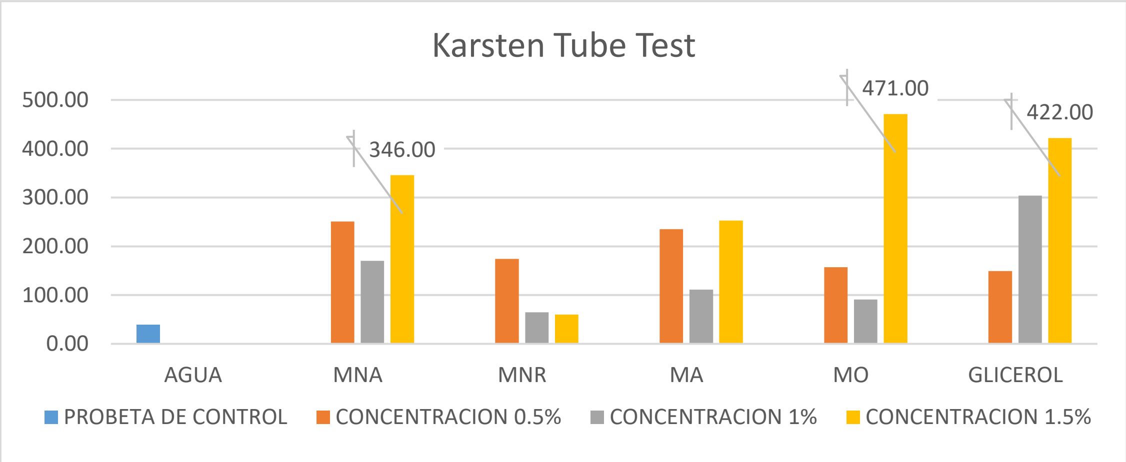

Figure 3. Blue bar represents water usage without any additives, orange bar represents 0.5 additive concentration, grey bar 1.0 and yellow bar 1.5 percentage. With the highest concentration of additives, especially with orchid mucilage (MO) and Glycerol the time required for water absorption increased significantly.

3.5.2 Italian Absorption Test

Absorption coefficients varied significantly:

- Highest: Control sample (5.24%), fresh nopal mucilage at 1.5% (3.92%), fresh nopal mucilage at 1% (3.71%)
- Lowest: Agave mucilage at 0.5% (1.37%), agave mucilage at 1.5% (1.54%)

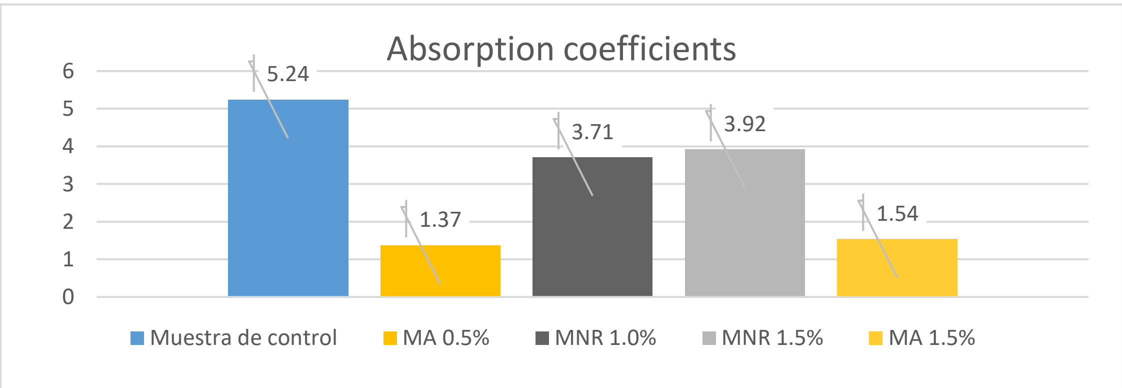

Figure 4. Blue bar represents water usage without any additives, with all the additives; especially with agave mucilage (yellow bar), the absorption coefficient of water was significantly reduced.

3.5.3 Total Immersion Test

- Most resistant: Agave mucilage at 0.5%, glycerol at 1% and 1.5% (all lasted 90 minutes).

3.6 Texture Analysis

Post-immersion texture analysis revealed varying disintegration patterns:

- (1) Fine texture: Control sample
- (2) Medium texture: Orchid mucilage at 0.5%, agave mucilage at 1%, aged nopal mucilage at 1%, agave mucilage at 1.5%, orchid mucilage at 0.5%
- (3) Coarse texture: Fresh nopal mucilage at 0.5%, glycerol at 1% and 1.5%
- (4) Very coarse texture: Agave mucilage at 0.5%

These results demonstrate significant improvements in tepetate properties with the addition of heteropolysaccharides and glycerol, particularly in terms of water reduction, compressive strength, and water resistance. The variations observed across different additives and concentrations suggest the potential for tailoring tepetate renders for specific restoration needs.

Figure 5. Plasters texture from finest to coarsest texture.

3.7 Climate-Specific Applications and Practical Implications

The results demonstrate significant improvements in tepetate properties with the addition of heteropolysaccharides and glycerol, particularly regarding water reduction, compressive strength, and water resistance. However, the practical application of these findings varies considerably depending on environmental conditions and regional constraints.

The practical implementation of these findings faces several limitations related to the seasonal availability of endemic plant materials. *Opuntia aciculata* typically produces optimal mucilage during specific growing seasons, while *Agave lechuguilla* harvesting must be carefully managed to ensure plant sustainability, as agave plants require several years to mature. *Cyrtopodium macrobulbon*, being an orchid species, presents the most significant availability challenges due to its limited natural distribution and the need for careful harvesting to avoid ecosystem disruption.

These seasonal constraints suggest that successful implementation would require establishing mucilage preservation protocols or developing cultivation programs for these endemic species. The use of glycerol as an alternative presents fewer seasonal limitations, as it is an industrial byproduct with consistent availability, making it particularly suitable for projects requiring year-round material access.

The economic viability of these enhanced renders varies by location and scale of application. While the raw materials are relatively inexpensive, the labor-intensive mucilage extraction process and the need for quality control in additive concentrations may increase overall project costs. However, the improved durability and reduced maintenance requirements demonstrated in the aging tests could offset these initial expenses over the lifecycle of restored structures.

4. CONCLUSIONS AND RECOMMENDATIONS

The results of this study demonstrate that the addition of heteropolysaccharides from endemic plants and glycerol can significantly improve the properties of tepetate renders, offering promising solutions for architectural conservation. These findings have important implications for the development of sustainable, locally sourced materials for restoration work.

- Water Reduction and Sustainability

One of the most significant outcomes of this study is the substantial reduction in water requirements across all additive mixtures. The ability to achieve up to 65% water reduction (with agave mucilage at 1.5%) not only improves the workability of the render but also aligns with sustainable construction practices by conserving water resources. This is particularly relevant in regions where water scarcity is a concern, and it contributes to the overall ecological footprint of restoration projects.

The water-reducing property of these additives can be attributed to their molecular structure and hygroscopic nature. For instance, the complex polysaccharide structures in plant mucilage can form a network that helps retain water within the render matrix (Guerrero Baca & Ávila Boyas, 2019). Similarly, glycerol's hygroscopic properties allow it to attract and hold moisture, reducing the amount of free water needed in the mixture.

- Mechanical Properties and Durability

The improvement in compressive strength across all additive mixtures, compared to the control sample, is a crucial finding. The exceptional performance of agave mucilage at 0.5% (42.09 kg/cm^2) and orchid mucilage at 1.5% (39.73 kg/cm^2) suggests that these additives not only bind the tepetate particles more effectively but also potentially create a stronger internal structure within the render.

The consistent strength observed with aged nopal mucilage and glycerol across all concentrations is particularly interesting. This stability could be beneficial in practical applications, as it suggests a wider margin of error in mixture proportions without significantly compromising strength. The aging effect on nopal mucilage, resulting in a predictable behavior, warrants further investigation into the chemical changes occurring during the aging process.

The improved cohesiveness observed in many of the mixtures, particularly those falling within the 6-9 cm range in the cohesiveness test, indicates enhanced suitability for use as base renders. This improvement could lead to better adhesion to substrates and reduced cracking, addressing some of the key limitations of unmodified tepetate renders.

- Water Resistance and Longevity

The water absorption tests reveal complex interactions between the additives and tepetate structure. The extended absorption times observed in the Karsten tube test for orchid mucilage, glycerol, and aged nopal mucilage at 1.5% concentrations suggest the formation of a more water-resistant surface. This property is crucial for protecting underlying structural materials from moisture damage, a common issue in historical buildings.

However, the variability in absorption coefficients observed in the Italian absorption test highlights the need for careful consideration when selecting additives for specific applications. The lower absorption coefficients achieved with agave mucilage at 0.5% and 1.5% indicate promising water-resistant properties, which could be particularly beneficial in areas prone to high humidity or rainfall.

The results of the total immersion test, showing extended resistance for agave mucilage and glycerol mixtures further support the potential of these additives in improving the durability of tepetate renders against extreme moisture conditions.

- Texture and Workability

The texture analysis following the immersion test provides insights into the disintegration patterns of the modified renders. The variation in textures from fine to extremely coarse suggests that different additives influence not only the water resistance but also the internal structure and particle bonding of the renders. This information could be valuable in selecting appropriate mixtures for different restoration contexts, balancing factors such as desired surface finish, required durability, and compatibility with existing materials.

Implications for Restoration Practices

The findings of this study have several important implications for restoration practices:

1. Customization: The varied performance of different additives allows for the customization of tepetate renders to meet specific restoration needs, such as high strength, water resistance, or workability.
2. Sustainability: The use of locally sourced, natural additives and industrial byproducts aligns with sustainable conservation practices, reducing the environmental impact of restoration work.
3. Cultural Preservation: By incorporating traditional materials like nopal and agave mucilage, this approach helps preserve and validate indigenous knowledge systems in modern conservation techniques.
4. Economic Viability: The improved properties of modified tepetate renders could potentially reduce maintenance frequency and costs in the long term, making it an economically viable option for restoration projects.

While this study provides valuable insights, there are limitations that future research should address. Long-term durability studies in real-world conditions are needed to validate the laboratory findings. Additionally, we suggest investigating the compatibility of these modified renders with different substrate materials commonly found in historical buildings.

Future research could also explore the molecular interactions between the additives and tepetate particles to understand the mechanisms behind the observed improvements. This could lead to more targeted modifications and potentially even better performing renders. This study demonstrates the significant potential of heteropolysaccharides from endemic plants and glycerol in improving tepetate renders for restoration applications. By enhancing strength, water resistance, and workability while reducing water requirements, these modified renders offer a promising, sustainable solution for the conservation of architectural heritage.

AUTHOR CONTRIBUTIONS

All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICS COMMITTEE APPROVAL

This study does not require any ethics committee approval.

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