

INTEGRATING HYDROXYAPATITE-BASED MATERIAL INNOVATION INTO DIGITAL HERITAGE SYSTEMS: A DATA-DRIVEN FRAMEWORK FOR SUSTAINABLE HERITAGE CONSERVATION

Alina MOȘIU^{1,2}, Iasmina ONESCU², Rodica-Mariana ION^{1,2,3,4}

¹ Doctoral School of Materials Engineering, University Valahia of Targoviste, 13 Aleea Sinaia, 130004 Targoviste, Romania

² Faculty of Architecture and Town Planning, Polytechnic University of Timisoara, 2 Traian Lalescu Street, 300223, Romania

³ ICECHIM, Research Group Evaluation and Conservation of Cultural Heritage, 202 Splaiul Independentei, Bucharest, Romania

⁴ Academy of Romanian Scientists, 3 Ilfov Street, 050044 Bucharest, Romania

E-mails: mosiu.alina@yahoo.com, iasmina.onescu@upt.ro, rodica.ion@valahia.ro

Abstract: Cultural heritage conservation is increasingly affected by environmental degradation, climate change, and intensified human pressures, which accelerate the decay of historic materials and call for more resilient and adaptive conservation approaches. In this context, growing attention is being given to the combined use of sustainable materials and digital technologies.

This paper explores an integrative framework that brings together materials science for heritage conservation, particularly hydroxyapatite-based materials, and digital documentation strategies. The approach builds on a synthesis of experimental and applied studies dealing with the physicochemical behavior, compatibility, and durability of hydroxyapatite-modified systems.

Particular attention is given to the types of data generated through such investigations, including microstructural features, moisture-related behavior, and environmental exposure conditions. The study discusses how these data can be organized and incorporated into digital environments such as HBIM and Digital Twin platforms, where they can support monitoring and interpretation over time.

The findings suggest that linking material-related data with digital models can improve the understanding of material performance and contribute to more informed conservation decisions. By outlining a conceptual pathway for data integration, the paper offers a starting point for further research aimed at connecting material innovation with digitally supported heritage conservation practices.

Keywords: HBIM; Digital Twin; hydroxyapatite-based materials; sustainable conservation; data integration; preventive conservation; heritage materials science; sustainable preservation

1. INTRODUCTION

Cultural heritage assets are increasingly exposed to a wide range of threats, including environmental degradation, climate-related risks, and intensified anthropogenic pressures (Azap, 2018). Climate change, recurring moisture variations, atmospheric pollution, salt crystallization, and extreme weather events contribute to the accelerated deterioration of historic materials (Sesana et al., 2021; Orr et al., 2021), while ongoing urban development further amplifies their vulnerability. Taken together, these processes place considerable pressure on conventional conservation practices and underline the need for more resilient, adaptive strategies.

In recent years, integrated approaches that combine materials science with digital documentation and long-term monitoring have gained increasing attention. Such frame-

works are now widely regarded as essential for preventive conservation, risk assessment, and more informed decision-making (Stylianidis & Remondino, 2016).

Among emerging material solutions, hydroxyapatite-based eco-materials have attracted particular interest due to their chemical compatibility with calcium-rich substrates and their capacity to improve microstructural cohesion and durability (Sassoni, 2018; Mosiu et al., 2025). Despite these advantages, the way in which such materials can be effectively integrated into digital heritage systems remains insufficiently explored (Sesana, 2018).

Although research on sustainable materials for heritage conservation has expanded significantly, it often develops along parallel lines. Studies tend to focus on material performance or on digital documentation, with limited interaction between the two. This separation makes it difficult to develop coherent, data-driven conservation strategies

that can address increasingly complex environmental conditions.

Within this context, a key research gap is the lack of structured frameworks to integrate experimental material data into digital heritage systems such as HBIM and Digital Twin environments.

The present study seeks to address this gap by proposing an integrative framework that connects eco-compatible conservation materials, particularly hydroxyapatite-modified systems, with digital documentation and preservation strategies. More specifically, the research aims to examine the role of these materials in ensuring compatibility and durability, to identify the types of data generated through their investigation, and to explore how such data can be incorporated into digital environments. In addition, the study proposes a conceptual workflow for integrating these datasets into HBIM and Digital Twin platforms and discusses their potential contribution to long-term monitoring and evidence-based conservation practices.

Rather than offering a finalized solution, the paper outlines a conceptual approach and should be understood as an initial step within a broader research effort. By bringing together material innovation and digital heritage systems, it aims to provide a basis for further work toward more resilient, data-informed, and sustainable conservation strategies.

2. CONCEPTUAL METHODOLOGY AND INTEGRATIVE FRAMEWORK

This study adopts a conceptual and integrative methodological framework aimed at connecting sustainable materials science with digital heritage preservation. Rather than presenting new experimental data, the approach is based on a structured synthesis of existing experimental and applied research related to hydroxyapatite-based conservation materials (Figure 1).

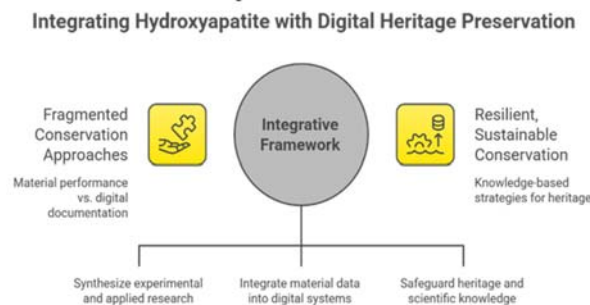


Figure 1. Conceptual methodological approach framework

The methodology consists of three main components:

1. Analysis of material performance;
2. Evaluation in relation to conservation principles;
3. Integration into digital heritage systems.

2.1 Material Performance and Conservation Context

The first component of the proposed framework examines both experimental and applied research addressing the physicochemical performance, compatibility, and durability of materials used in cultural heritage contexts. Particular attention is given to mineral substrates, especially lime-based mortars and limestone, which are widely encountered in historic structures.

In this regard, several key parameters are typically considered, including microstructural cohesion, pore structure evolution, resistance to salt crystallization, moisture transport behavior, and performance under freeze-thaw cycles (Mosiu et al., 2025). Bringing together evidence from laboratory investigations and in situ observations makes it possible to identify recurring performance patterns, as well as the main limitations associated with hydroxyapatite-based treatments. These aspects are essential for assessing their potential role within conservation strategies.

At the same time, recent work in heritage materials science has increasingly turned toward eco-compatible solutions intended to address the shortcomings of traditional consolidation and repair methods. Lime-based formulations, mineral additives, and bio-inspired materials have been extensively studied, particularly in relation to their compatibility with historic substrates and their response to environmental stress (Ramirez et al., 2021).

Recent research in heritage materials science increasingly focuses on the development of eco-compatible solutions designed to overcome the limitations of traditional consolidation and restoration methods. Lime-based formulations, mineral additives, and bio-inspired materials have been widely investigated for their compatibility with historic substrates and their improved environmental performance (Ramirez et al., 2021).

Beyond their technical performance, hydroxyapatite-based materials must also be evaluated in relation to core conservation principles. These include compatibility, authenticity, minimal intervention, reversibility, and long-term sustainability. Considering these aspects ensures that material innovation does not operate in isolation, but remains consistent with established conservation practice.

2.2 Integration of Material Data into Digital Documentation Systems

In addition to evaluating materials performance and ensuring alignment with conservation principles, contemporary heritage conservation increasingly relies on systematic digital documentation, structured data management, and evidence-based decision-making processes. The integration of material-related information into digital environments represents a key step toward developing coherent and traceable conservation strategies.

Interventions involving hydroxyapatite-based conservatio

n materials generate various types of data, including: physicochemical properties (porosity, composition, microstructure), hygric behavior (moisture transport, capillary absorption), environmental exposure parameters, and conservation treatment records.

These data can be structured and integrated into digital heritage systems such as HBIM platforms using layered information models. Each material parameter can be associated with specific building components, allowing traceability and monitoring over time (Remondino & Campana, 2014). When they are structured in a clear framework, data on material performance can support comparative analyses, performance assessment, and the evaluation of intervention effectiveness under different environmental conditions. This approach enhances the transparency of conservation processes, ensures the traceability of interventions, and strengthens interdisciplinary collaboration between heritage conservation, materials science, and digital technologies.

The integration process involves: data acquisition (laboratory + in situ), data structuring (material attributes, metadata), storage in digital repositories, linking with geometrical models (HBIM).

By correlating data on material behavior, environmental exposure conditions, and outcomes of conservation treatments, digital platforms can support long-term monitoring, risk scenario evaluation, and the development of adaptive conservation strategies. From this perspective, digital conservation systems are no longer limited to passive documentation but become active components of the conservation process by integrating scientific data from materials research into knowledge-based strategies adapted to current heritage challenges.

This approach enables comparative analysis, performance tracking, and evaluation of intervention efficiency under varying environmental conditions.

2.3 HBIM and Digital Twin Integration

The Heritage Building Information Modelling (HBIM) and Digital Twin (DT) are more than digital representations; they are data-enriched digital models that integrate material-related conservation data into digital workflows.

Building upon the previous section, HBIM and DT technologies represent operational environments for implementing this integration.

HBIM models allow the association of material data with specific architectural elements, while DT systems enable dynamic monitoring by incorporating real-time or periodically updated data.

In the case of existing and historic buildings, the conventional BIM processes are not enough, so the HBIM methodology adapts the models to become central repositories for holistic conservation data, incorporating geometry,

structural particularities, material characteristics, and damage patterns. In the context of innovative materials, such as the hydroxyapatite-modified mortars, HBIM provides a framework for assessing not only the physical properties of existing materials and decay level, but also the physicochemical properties and long-term performance of proposed conservation materials, to support more sustainable interventions (Murphy, 2009). The workflow specific to HBIM is characterized by three steps: data acquisition (survey), processing, and semantic modelling phases (Fig. 2).



Figure 2. From visual survey to 3D modelling. Martin Gmeinhardt Palace in Timisoara, Romania

In the specific case of heritage buildings, the data collection process combines multiple tools, such as direct survey and measurement, photogrammetric image-based modelling, vectorization of historical drawings, and 3D laser scanning (Jouan, 2019). The models generated from the surveys provide the geometric information for building parametric or object-based representations of walls, vaults, roofs, and decorative elements that can be later associated with specific material properties (Fig. 3).

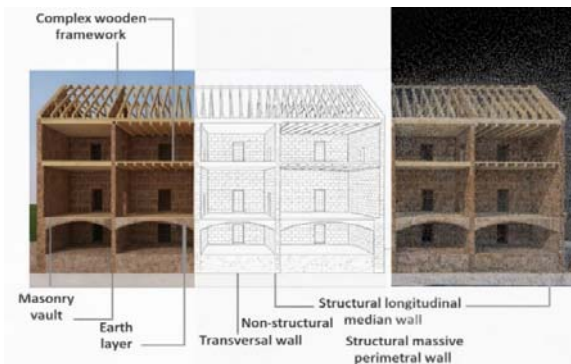


Figure 3. Integrating geometry and structural particularities in the digital model. Typology of heritage masonry buildings in Timisoara, Romania

Within the HBIM framework, information related to mortar types, the presence of hydroxyapatite additives, porosity, moisture behavior, and existing conservation treatments can be associated with specific components of the 3D model. This enables the creation of an integrated environment in which laboratory results, in situ measurements, and intervention monitoring data can be systemat-

ically recorded, linked, and analyzed over time (Kamaruzaman, 2019). Although there are multiple advantages, there are also challenges in HBIM adoption for conservation, as the surveys are not always heterogeneous, the processes are time-consuming, and the operability with other heritage systems is limited (Penjor, 2024). While HBIM is able to provide the geometric basis, the Digital Twin framework connects it to environmental components, structural health indicators, and updated digital surveys to detect real-time deformation and decay of areas treated with hydroxyapatite-based mortars or other conservation treatments (Cosovic, 2022).

Integrating innovative materials into HBIM and Digital Twin systems allows a deeper understanding of the materials' behavior, showing how material innovation and conservation practices can work together for a more sustainable approach. Considering frameworks such as HBIM and Digital Twin in the heritage conservation practice represents the link to a more innovative and sustainable intervention proposal, which is based on materials compatibility, long-term monitoring, risk assessment, and motivated decision-making. Figure 4 illustrates a conceptual workflow in which material data are collected, structured, and integrated into HBIM environments, forming the basis for Digital Twin applications. This workflow represents a structured implementation pathway of the proposed framework, supporting data integration, long-term monitoring, and conservation decision-making.

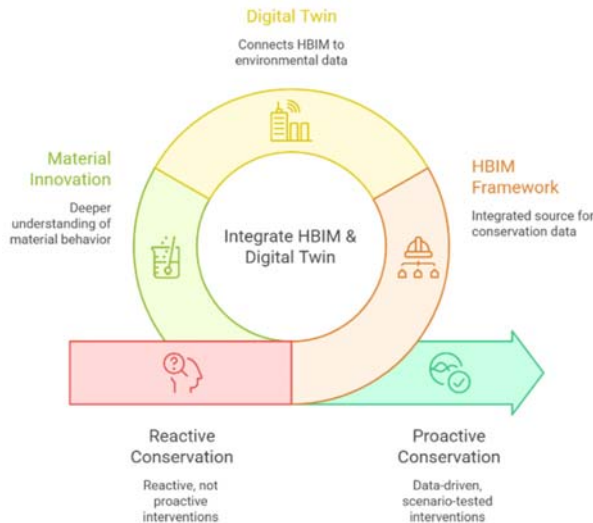


Figure 4. Conceptual workflow for integrating material-related data into HBIM environments, enabling Digital Twin applications for monitoring and conservation management

3. DISCUSSION

The proposed integrative framework highlights the importance of bridging the gap between material science and digital heritage preservation. By linking experimental data with digital heritage systems, conservation interven-

tions can become more transparent, traceable, and scientifically grounded. Digital tools should be used not only for documentation and visualization, but also for assessing material behavior and long-term performance, enabling preventive conservation strategies (Sesana et al., 2021; Orr et al., 2021).

Although challenges related to the lack of standardized protocols for conservation material data collection remain, they also highlight a clear direction for future research, namely the development of shared digital frameworks for interdisciplinary collaboration.

Moreover, the relationship between material innovation and conservation ethics is complementary, because hydroxyapatite-based solutions are designed to enhance traditional materials' properties, not to replace them. This is why, especially when it comes to risk-prone contexts, the physical and historical integrity of the heritage assets is not altered, but their durability is improved.

A key gap identified is the limited integration between research in conservation materials science and digital heritage workflows. The digital tools are mostly used for visualization and documentation, but not necessarily for performance assessment.

The heterogeneity of historic buildings, the variability of environmental conditions, and different institutional practices represent important limitations for the large-scale implementation of the proposed approach. While this limitation is clear, it could also represent another future research direction for the development of standardized digital protocols and interdisciplinary collaboration between material scientists, conservators, and digital heritage specialists. When sustainability is considered in the fields of heritage preservation and urban planning, more resilient solutions can be developed (Belkhir, 2026).

4. CONCLUSIONS

This study emphasizes the need for an integrative approach in heritage conservation, combining sustainable materials with digital technologies. Hydroxyapatite-based materials represent a promising direction for eco-compatible interventions, while digital systems such as HBIM and Digital Twins provide the necessary infrastructure for long-term monitoring and data management.

Moreover, hydroxyapatite-based solutions can contribute to the generation of a scientifically valuable database that can be systematically integrated into digital heritage systems. When a link among materials science, conservation science, and digital heritage workflows is created, the conservation practices can become more evidence-based and resilient, especially for heritage assets exposed to risk factors.

This paper contributes to current heritage conservation discourse by bridging the gap between sustainable material innovation and digital heritage preservation, thereby

supporting the development of resilient, data-driven conservation strategies adapted to climate-related risks. The proposed integrative perspective supports long-term knowledge preservation, informed decision-making, and the development of conservation policies aligned with open-access principles and the challenges of heritage at risk.

Future research should focus on implementing and validating this framework through case studies and real-world applications.

Ultimately, the integration of material science and digital heritage systems represents a critical step toward the development of adaptive, knowledge-driven, and sustainable strategies for the long-term conservation of cultural heritage.

ACKNOWLEDGEMENTS

This work was supported by a grant of the Romanian Ministry of Education and Research, National Authority for Scientific Research (ANC), Nucleu project PN 23.06.02.01 – InteGral.

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