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STRENGTHENING THE RESILIENCE OF ARCHITECTURAL HERITAGE, WATERPROOFING AS A PREVENTIVE CONSTRUCTION TECHNIQUE AT THE NATIONAL MUSEUM OF BARDO-ALGIERS

Dr. Lahlou Siham

Institute of Architecture and urban planning, Saad Dahleb University, Blida, Algeria. OVAMUS laboratory: Observatory of the city & development: urban and space change Lahlousihem@gmail.com

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Abstract

This paper examines the importance of strengthening the resilience of architectural heritage through preventive construction techniques, focusing on waterproofing at the National Museum of Bardo in Algeria. In the face of growing environmental challenges, historical structures are at risk from issues such as flooding and humidity. The adoption of preventive techniques is essential to safeguard these buildings and their collections.

Waterproofing involves designing effective drainage and protection methods to prevent water accumulation around the foundations, thus avoiding damage. The study presents the specific methods implemented at the Bardo Museum, which houses a valuable collection of artifacts.

The results show that the implementation of these systems has significantly reduced flooding risks and improved the durability of the structures. These interventions use sustainable materials, respecting the environment.

In conclusion, this paper emphasizes the importance of raising awareness among decision-makers regarding preventive techniques. Preserving cultural heritage requires a proactive approach to anticipate and manage risks, ensuring the sustainability of historical sites for future generations.

Keywords: Resilience, Heritage, Waterproofing, National Museum of Bardo.

Introduction

The Palace of the Nation al Museum of Bardo, built in the 19th century, is an exceptional example of Islamic architecture in Algeria. As a site of great historical and cultural value, it embodies a rich heritage. However, the issue of humidity poses a major challenge

for its preservation. Water infiltration, exacerbated by changing climatic conditions and defects in existing drainage systems, threatens the structure of the palace.

To address these challenges, it is crucial to implement effective methods for combating humidity in order to preserve the structure and the artworks it houses. Waterproofing the palace is an essential priority, allowing for protection against infiltration and rising damp. Additionally, the use of salt converters proves to be an innovative solution, transforming harmful elements into non-hygroscopic components and thus enhancing the durability of the walls while preserving their ability to breathe. This integrated approach goes beyond the physical restoration of the palace; it fits into a broader vision of resilience in architectural heritage. Resilience, in this sense, involves not only the protection and conservation of existing structures but also their adaptation to contemporary and future challenges.

Research aim

The objective of this paper is to explore in depth the strategies implemented to combat humidity in the Bardo Palace, while highlighting the importance of resilience in architectural heritage. It aims to demonstrate how an integrated approach, combining modern techniques with respect for traditions, can ensure the sustainability of this cultural treasure for future generations.

Material and method

Research design

This study used a single-site case study design with a before–after (quasi-experimental) evaluation to assess the effectiveness of waterproofing treatments applied at the National Bardo Museum. The approach was intervention-based and implemented in situ, combining an initial diagnostic phase, targeted remediation, and systematic post-treatment monitoring under real museum conditions.

Preliminary diagnostic survey and area selection

A preliminary survey was performed through systematic visual inspection of the museum's structures. The inspection targeted and documented the most humidity-affected zones by recording:

- wall dampness and moisture staining,
- presence and extent of efflorescence,
- and other visible humidity-related manifestations and degradation patterns. Treatment areas were selected based on the severity and distribution of these observations.

Hygrometric

monitoring: baseline phase (pre-treatment)

To establish baseline conditions, hygrometers were installed in strategic locations within the museum.

Measurements included:

- indoor air relative humidity, and
- wall surface relative humidity at the critical damp-affected areas.

The monitoring setup was designed to be representative while adapting to site constraints. Approximately two hygrometers per room were used—typically one for indoor air and one for wall surface—with the exact number and placement depending on room surface area and the degree of contamination/dampness.

Humidity monitoring was carried out over a 24-month baseline period prior to treatment. Sensors were installed in the following rooms:

- Maghrebian Room
- Archive Room
- Prehistoric Room
- Weapons Room

Waterproofing intervention (targeted remediation)

After identification of critical humidity zones and establishment of baseline conditions, targeted waterproofing interventions were applied. Treatments were selected to reduce moisture presence and/or moisture uptake in building materials while ensuring compatibility with the historic structure of the museum. The intervention strategy focused on the previously identified damp-affected areas, using appropriate application techniques to limit any potential impact on the architectural fabric.

Post-treatment monitoring phase

Following completion of the waterproofing interventions, monitoring continued for 12 months to evaluate treatment performance. Relative humidity was measured again using the same monitoring logic as in the baseline phase:

- measurements at wall surfaces and
- measurements of indoor air,

In parallel, scheduled visual inspections were conducted to observe changes in damp-related conditions (including stabilization or reduction of efflorescence and other humidity manifestations) in the treated zones.

Data analysis and evaluation criteria

Data were processed using descriptive statistics to characterize:

- trends in relative humidity over time,
- baseline vs. post-treatment changes in humidity behavior,
- and the degree of stabilization/reduction after treatment.

Effectiveness was interpreted through comparison between pre- and post-intervention humidity patterns, supported by visual observations from the treated areas.

Author involvement and research team participation

During the full study period, the author was involved at the National Bardo Museum for approximately 2.5 years as a member of the research team. This participation covered the implementation of the monitoring protocol and the continuity of site follow-up, with particular involvement during the middle phase of the data collection period, contributing to the maintenance of the hygro-metric measurements and the integration of observations required for the subsequent waterproofing evaluation.

The following diagram (Figure 1) summarizes the key steps of the methodology, illustrating the process in a structured and logical way.

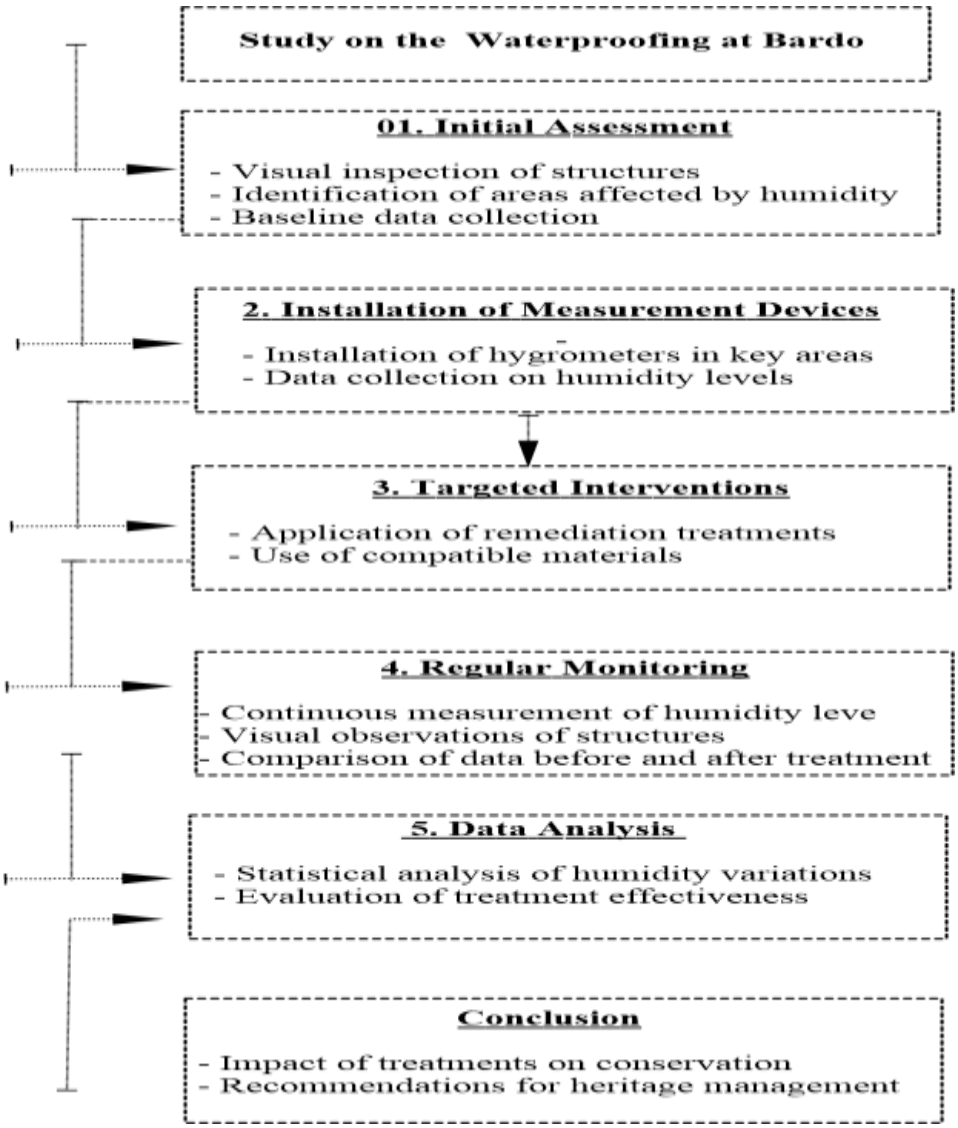

Figure 1: Schematic Representation of Materials And Methodology Processes (LAHLOU, 2024)

Architectural Heritage and Associated Risks: Context, Challenges, And Preservation Strategies in Algeria.
Walker et al. describe resilience as "the capacity of a system to absorb disturbances and reorganize itself while implementing changes that allow it to maintain its core functions, structures, and identity—in essence, to remain within the same domain" [Holling, C.S, 1986].
Thus, to comprehend a system's evolution in terms of its resilience, one must consider the adaptive cycle model, which suggests that most dynamics of Socio-Ecological Systems (SESs) progress through four stages: the growth and exploitation phase (r), the conservation phase (K), the release phase (Ω), and the reorganization phase (α) [Holling, C. 1986].
The resilience of architectural heritage in Algeria is crucial for preserving its cultural and historical identity. The colonial context exerted pressures on this heritage, as evidenced by the [Feuillets d'El- Djezaïr," published between 1910 and 1962 by the Comité du Vieil Alger]. These publications are a valuable source for documenting Algerian heritage, emphasizing the importance of preserving historic buildings and the picturesque neighborhoods of Algiers. Founded in 1905, the Comité worked against the degradation of the city and for the conservation of its architectural heritage [Hueber, J. 2018].
Ottoman architecture in Algeria has long been neglected by colonial authorities. However, architects like A. Ravoisié and E. Duthoit began documenting these buildings in the 19th century, highlighting their aesthetic and historical value. It wasn't until the late 19th century that significant efforts were made to preserve these monuments, an essential awareness given the current context where resilience against environmental threats is vital [Cherif, N. 2016.].
Sustainable development in the Mediterranean emphasizes the preservation of cultural heritage as a key element. Conservation strategies must integrate sustainable approaches that consider environmental risks, including floods and humidity, which threaten the integrity of ancient structures in Algeria. The National Heritage Institute in Algeria regularly publishes studies on these challenges, addressing climatic conditions and strategies for protecting historic buildings [Hueber,J. 2018].
The preservation of architectural heritage is essential for maintaining a country's cultural identity. In Algeria, this heritage represents an invaluable legacy that reflects past civilizations and the evolution of architectural styles over the centuries. It encompasses not only historic buildings but also monuments and archaeological sites that shape the cultural landscape and collective memory of a nation [Hueber, J. 2018].
Ordinance No. 67-281 of December 20, 1967, concerning the protection of historical sites and monuments, emphasizes that these elements are an integral part of national heritage and under the protection of the state. However, this heritage is increasingly threatened by various factors, such as climate change, which intensifies extreme weather events, aging infrastructure, and rapid urbanization. Flooding, in particular, poses a major risk, causing significant structural damage to buildings and the art collections they house [Cherif, N. 2016].
The National Museum of Bardo, located in Algiers, is an emblematic example of the richness of Algerian architectural heritage. This former Moorish villa houses a vast collection of artifacts ranging from prehistory to the Islamic period. Its geographical location, near areas susceptible to flooding, exacerbates the risks it faces.
Therefore, it is crucial to protect this architectural heritage to ensure the conservation of artworks and the transmission of cultural heritage to future generations [Images Défense, 2014].
Waterproofing: Protection Of Heritage in Algeria
Waterproofing refers to a set of techniques and measures aimed at protecting buildings and structures, particularly those of cultural heritage, from water-related risks such as flooding and moisture. This approach is crucial for the conservation of historical edifices, as it helps preserve their structural and aesthetic integrity against environmental threats.
In the Algerian context, waterproofing often involves the use of effective drainage systems, the application of waterproof materials, and sometimes the elevation of building foundations.
These measures are essential to ensure the durability of heritage sites, which are often exposed to harsh climatic conditions and flood risks [Ouagueni, Y. JUNE 2015].

Waterproofing is also linked to a growing awareness of the importance of preserving cultural heritage. Indeed, the degradation of historical sites in Algeria, due to a lack of maintenance and unfavorable environmental conditions, underscores the need to adopt effective protection strategies [Guerroudj, T. (2000)].

Thus, waterproofing is not limited to technical interventions but is part of a comprehensive approach to enhancing and safeguarding Algeria's cultural heritage [Law No. 98-04 on the Protection of Cultural Heritage].

This strategy is essential for the preservation of architectural heritage in Algeria. It protects historical buildings from the harmful effects of moisture and weather conditions. Algeria's architectural heritage, rich and diverse, is often vulnerable to environmental risks such as heavy rains and flooding, which can cause irreversible damage.

By preventing water infiltration, waterproofing helps maintain the structural and aesthetic integrity of historical buildings. For instance, in sites like the Casbah of Algiers, moisture can severely affect ancient structures, leading to degradation that compromises their heritage value. By protecting these buildings from the elements, this approach also helps preserve their historical and cultural significance. Waterproofing interventions enable the conservation of original materials, thus ensuring the authenticity of the sites.

Waterproofing techniques must be applied respectfully, utilizing methods and materials that honor traditional architecture. This not only ensures the protection of heritage but also supports the continuity of local craftsmanship. Sites like the ruins of Timgad and the Casbah of Algiers illustrate the importance of this strategy, as they require specific measures to address moisture risks.

In summary, waterproofing is crucial for the conservation of architectural heritage in Algeria. It plays a key role in protecting historical buildings from moisture-related risks, ensuring their transmission to future generations and preserving the country’s cultural identity.

The National Bardo Museum: Heritage and Architectural Beauty

The National Bardo Museum is an ancient residence, dating from the late 17th to early 18th century, that was buried in the Algerian countryside during the Ottoman Regency. Over the years, the house changed hands among nobles and governors, who enriched the building with successive architectural and artistic additions and modifications.

Today, the National Bardo Museum is dedicated to prehistory and ethnography, housing several collections of prehistoric, Paleolithic, and Neolithic objects. The majority of the pieces come from excavations conducted in Algeria, while some have been acquired through exchanges with foreign institutions.

Classified as a historical monument since 1985, the museum was once a Moorish villa before being transformed into a museum in 1930. The Bardo villa is part of a larger complex known as the Mustapha Supérieur estate. It is located in the heart of Mustapha Supérieur, specifically along the old Blida Road.

The villa was designed as a private residence, reflecting a sense of intimacy that underpins the organization of space. Its garden, adorned with beautiful plants, blends tropical species with local flora. It features lush vegetation, including fruit trees and ornamental plants, as well as a nursery. The entire site is situated at a bend, giving it the appearance of a passageway, at 3 Franklin Roosevelt Street, right in the heart of Algiers.

The National Bardo Museum of Algiers consists of two distinct types of constructions: the traditional palace, which forms its historical core, and the colonial extensions designed by Pierre Joret starting in 1879. The façade of the palace is characterized by elegant lines and refined ornaments, showcasing local craftsmanship. The stone walls are often decorated with geometric patterns and colorful tiles, typical of Islamic architecture [Ouagueni, Y. 2015].

At the entrance, there is a spacious courtyard surrounded by walls adorned with tiles. This multifunctional courtyard, although not central, serves as a point of convergence and circulation, providing a transitional space between the outside and the inside of the museum. The courtyard is embellished with lush gardens and fountains that create a soothing atmosphere [Guerroudj, T. 2000].

The courtyard is divided into two sections, each characterized by distinct elements. In the center of the first section, a sculpted marble fountain rises above an octagonal basin. In the second section, there is a large rectangular basin known as the 'women's basin.' The courtyard is surrounded by three galleries, one of which

extends from the pavilion of the favorite. Just behind this gallery, but set back, stands the Diwan, an elevated open-air salon that is one and a half meters above the courtyard.

The palace of bardo: between ambitious restoration and urgent interventions

Since 2006, the Palace of Bardo in Algiers has been at the heart of an ambitious restoration effort, prompted by the urgent need to address humidity issues threatening the structure and collections of the monument. This initiative was launched in response to a thorough assessment of the environmental and structural conditions of the site, which revealed that water infiltration represents one of the most significant threats to the palace's integrity.

The waterproofing of the buildings constitutes an emergency phase in this restoration process. It aims to prevent potential damage caused by humidity by implementing immediate and effective solutions. Among the measures considered are the installation of peripheral drainage systems, rehabilitation of the terraces, and repair of cracks in the walls. These actions are essential to halt the progression of infiltrations and protect the building from the devastating effects of water.

This waterproofing project, although a response to a crisis, is part of a comprehensive heritage preservation strategy. By proactively addressing the challenges posed by humidity, this operation aims not only to ensure the longevity of the Palace of Bardo but also to preserve its history and ensure its accessibility for future generations.

Causes and humidity issues at the palace of bardo

Rising humidity comes from the ground and ascends through the walls via capillarity. This phenomenon is often exacerbated by a lack of foundation protection. This form of humidity leads to material degradation, particularly salt efflorescence on the walls. Rainwater infiltration primarily occurs through buried walls, often due to the absence of effective drainage systems.

Additionally, watering the adjacent green spaces can contribute to this problem. Water seeping into the walls can cause structural damage, mold growth, and pose risks to the safety of the displayed artworks.

This type of humidity forms when warm, moist air comes into contact with cold surfaces, causing water vapor to condense. Waterproof coatings can worsen this phenomenon by preventing the natural evacuation of moisture. Condensation can lead to blistering in the coatings and promote mold growth, affecting indoor air quality.Various technical disorders can contribute to humidity, such as the rupture of rainwater drainage systems or the degradation of waterproofing complexes on terraces. These technical issues exacerbate humidity conditions and can lead to high repair costs if not addressed promptly. [figure 2,3]

Figure 2: The Degradation Of A Façade Due To The Rupture Of The Rainwater Drainage System (National Museum Of Bardo).

Figure 3: (Left) Mold in Interior Spaces Affecting the Tiles + Degradation of The Coatings. (Right) Stripping of The Damaged Coatings (National Museum of Bardo).

Waterproofing Measures

To address these humidity issues, several solutions can be considered. The walls of Bardo are made of traditional masonry, characterized by its porosity to air and water vapor, resulting in a phase- shifted thermal and hygrometric conduction and radiation, providing pleasant temperatures year- round. However, humidity in the walls becomes detrimental when it, for various reasons, becomes pathological: mold, blistering of the coatings. As a result, all waterproof coatings have been removed and replaced with breathable ones. Finally, an effective waterproofing system has been implemented to prevent rainwater infiltration into the floors and masonry.

On one hand, groundwater and certain construction extensions have weakened parts of the buildings. Due to the lack of drainage at the base of the retaining wall on Boulevard Franklin Roosevelt, groundwater—well-known for its abundance in the Telemly region—has managed to penetrate the lower levels of the building.

Moreover, the construction of sewage networks during the colonial era, which were connected to a soakaway identified during the excavations of the upper courtyard, has long been the source of water infiltrations at the sqifa, which would become flooded every winter.

To combat rising humidity from the ground along the buried masonry and lateral infiltrations, the following solutions have been implemented:

- Installation of peripheral PVC drains at the base of the foundations, connected to a system of inspection chambers leading to the final discharge.
- Creation of ventilated walls (former garden basin and Moorish café). [figure 4]

Figure 4: Construction Of Inspection Chambers for Groundwater Drainage at The Upper Courtyard. (National Museum of Bardo).

The drainage work was carried out at depths sometimes reaching three meters. The goal of the peripheral drainage is to prevent water accumulation around the foundations. This involves installing drainage systems that redirect rainwater away from the walls, thereby minimizing infiltrations. [figure 5]

Figure 5: Installation Of the Drain at The Base of The Foundation on The Franklin Roosevelt Street Side. (National Museum of Bardo)

Wall Drying Strategies, Combatting Humidity

Despite all the drainage solutions implemented, the moisture accumulated over years in the walls, enriched with hygroscopic salts, persists. Humidity issues affect several areas of the museum, and to ensure its functionality after the work, an Algerian-Belgian company led by Dr. Jean Guy Gilles, specializing in the renovation of historic buildings, was engaged. This company conducted drying work on the affected walls and provided a detailed report on its interventions.

The issue of humidity in a building must be examined holistically, as multiple sources of moisture can cause damage. Each type of humidity requires a specific approach: for instance, rising damp necessitates the injection of a waterproofing solution at the base of the masonry. In the case of the Bardo Museum, it is crucial to consider the walls in contact with the ground and apply a waterproof treatment across the entire surface. (Dr. Jean Guy Gilles)

The hygroscopic salts present in the masonry complicate the treatment process, making it necessary to accurately assess their concentration and apply appropriate treatments. To restore the museum, a set of techniques has been used to address both rising and lateral humidity, while managing the significant presence of salts.

To neutralize hygroscopic salts, the use of salt converters modifies nitrates, chlorides, and sulfates into non-hygroscopic salts, while releasing NO2 molecules. This chemical process transforms soluble radicals into insoluble elements, which are more resistant to acids.

These converters, in aqueous form, allow for deep action through spraying or injection, increasing the hardness and consistency of the masonry without altering its breathability. They also contribute to the sanitation of the wall by destroying certain microorganisms.

Additionally, anti-salt barriers must be installed to protect the new coatings from residual salts, as complete removal of hygroscopic salts is not possible. In the context of the renovation of the Bardo Museum, the application of these techniques was essential for effectively addressing both rising and lateral humidity, as well as the significant presence of salts.

These methods enable the museum to regain an optimal appearance while maintaining an adequate humidity level for heritage conservation. This approach has preserved the building and its heritage while ensuring its functionality. For the Bardo Museum, a systematic approach is essential for effectively addressing this issue.

First, a thorough diagnosis is conducted to identify the sources of humidity and the types of salts present, which allows for the determination of the most suitable treatments. Rising moisture requires specific solutions, such as injecting waterproofing products into the walls, performed by drilling at the base of the masonry to create a watertight barrier.
It is also crucial to apply a waterproofing agent to all walls in contact with the ground to prevent water penetration and protect the structure. Therefore, the injection must be carried out in perfectly masonry walls, sometimes requiring the craftsman to carry out masonry repairs. [figure 6]

Figure 6: Drilling And Injection of a Waterproofing Solution (Prehistory Room) (National Museum of Bardo)
The management of hygroscopic salts is another important step, requiring an accurate assessment of their concentration. Specific treatments, such as washing or the application of suitable products, may be necessary to reduce their impact. To simultaneously address both rising and lateral moisture, a combination of techniques is often implemented to ensure a comprehensive and effective approach. [figure 7]

Figure 7: Moisture Treatment Wall: Anti-Salt Barriers) (National Museum of Bardo)

Finally, regular monitoring after the interventions is essential to ensure that the implemented solutions remain effective and to detect any potential return of moisture. These strategies aim not only to dry the walls but also to preserve the integrity and heritage of the museum while ensuring its long-term functionality.

Conclusion

The management of humidity in the walls of the Bardo Palace is a crucial issue for preserving its integrity and architectural heritage. Given the persistent moisture exacerbated by hygroscopic salts, it is imperative to adopt a systematic and integrated approach that illustrates the resilience of heritage.
A thorough diagnosis allows for the identification of moisture sources and the definition of appropriate treatments, such as the injection of waterproofing solutions and the application of specific treatments on walls

in contact with the ground. These interventions aim to create effective barriers against rising damp, thereby enhancing the durability of the structure.
The management of hygroscopic salts also requires special attention, with targeted methods to minimize their impact. The combination of techniques to simultaneously address various forms of moisture demonstrates the necessary adaptability in facing environmental challenges.
Finally, regular monitoring after the interventions is crucial to ensure the longevity of the implemented solutions. This vigilance contributes to the resilience of the Bardo Palace, ensuring not only the protection of its heritage but also its cultural and functional role within the community.
In summary, these drying strategies do not merely restore the building; they strengthen its resilience against future challenges, highlighting the importance of preserving our architectural heritage for generations to come.

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