Restoration and Sustainability of Earthen Architecture: Ksar of Khanguet Sidi Nadji in the Algerian Sahara as a Case Study

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Abstract

Earthen architecture has a rich history of providing durable and sustainable shelter for humans. However, many of these heritage sites are now facing abandonment and obsolescence. Kasr Khanguet Sidi Nadji in the Algerian Sahara is not exempt from this reality. To address this critical situation, we propose a sustainable, eco-friendly, and cost-effective solution for the restoration of the Ksar that takes into account the needs of its residents and its heritage value. Our approach utilizes the anastylosis method which implies that we reuse original on-site components as building materials whenever possible. We introduce new materials only when necessary after subjecting them to rigorous testing and control. Additionally, we take into account the complex challenges of human, natural, and technical factors involved in the restoration process, offering a practical solution to restore and preserve the earthen heritage of the Ksar while benefiting its residents.

1. Introduction

Algeria is a vast country located in North Africa, with a total land area of approximately 2,381,741 km$^2$ [UNSD]. The country has a rich and recognized heritage, with 7 World Heritage Sites and 10 Intangible Cultural Heritage elements [UNESCO]. The Sahara covers more than 80% of its territory, making it home to a unique ecosystem and diverse cultures that have adapted to its challenging conditions. The Sahara is also rich in architectural heritage, which is remarkably featured in the cities that were once key points of the trans-Saharan trade. These cities played a crucial role as trade hubs for caravans crossing the desert to reach sub-Saharan Africa and have left behind remarkable examples of earthen architecture [Côte, 2005].

One of the architectural legacies of the Saharan nomadic movements are the ksour, which are fortified villages and settlements that served as necessary stops for caravan trade routes. These compact settlements offered protection from harsh climates and human incursions, creating striking unitary groups, particularly in mountainous areas where they were sheltered from the force of rivers. Among the rare historic earthen architectural structures of this kind in Algeria, Ksar Khanguet Sidi Nadji stands out as a unique complex urban structure influenced by Ottoman design [Figure 01] and represents an invaluable Saharan city [Abbas, 2004]. The Ksar in question, a combination of several architectural styles, has served as a home, a place of worship, and an economic hub for its residents, making it a perfect example of bioclimatic adaptation in architecture. This notion involves designing and constructing buildings that are adapted to the local climate and environment, using passive design strategies to minimize energy consumption, reduce environmental impact, and enhance occupant comfort and well-being [Balaguer et al., 2019]. Ksar Khanguet Sidi Nadji constitutes a formidable identity and tourism capital to preserve for future generations. However, this heritage is currently endangered and threatened with disappearance.
This work aims to develop a restoration protocol for Ksar Khanguet Sidi Nadji that considers the diverse human, natural, and technical factors that have contributed to its deterioration, while preserving its cultural heritage and meeting the needs of its residents. Our approach is based on anastylosis, which involves prioritizing the reuse of original on-site components to reconstruct the structure of the Ksar. Through this restoration protocol, we also seek to demonstrate the continued practicality and sustainability of earthen architecture as an eco-friendly and cost-effective solution for housing in the Saharan context. Our work highlights the importance of careful planning and informed decision-making in the preservation of cultural heritage, and we aim to provide a useful model for future restoration projects.

The article is divided into six sections. Section 2 provides an introduction to Ksar Khanguet Sidi Nadji, highlighting its architectural, historical, and cultural significance. Section 3 discusses earthen architecture and its relevance to the Saharan context in general and Ksar Khanguet Sidi Nadji in particular. To facilitate its restoration, Section 4 presents an assessment of the Ksar, identifying the various factors that have contributed to its current state of deterioration. Section 5 details the restoration protocol for the Ksar, with a particular focus on the adaptation of the anastylosis method. Finally, Section 6 concludes by summarizing the main points of the article, offering final thoughts and recommendations, and suggesting areas for further research and action.

2. Ksar Khanguet Sidi Nadji

Preserving places of memory is crucial for maintaining collective identity for future generations (Dinkel, 1997). Keeping this in mind, Ksar Khanguet Sidi Nadji is not only an integral part of the natural, historical, architectural, and urban heritage of the Oriental Zab region and the Algerian Sahara, but also a living testimony to the know-how and identity of the entire country. Due to its significance, the Ksar was designated as a natural heritage site in 1923 during the French era. Later, in 1967, it was added to the national heritage list by Algerian legislation (Nasri, 2007; Makhloufi, 2010).

Ksar Khanguet Sidi Nadji is a fortified village situated at an altitude of 254 m between the foothills of the Aurès Mountains and the Sahara (Figure 02), specifically near the provincial borders of Biskra and Khchenhela, and adjacent to a river called Oued El Arab (Figure 03). Its construction in its current form began in the 16th century. The region features a vast oasis with thousands of palm trees and some fields of barley. The Ksar is a very dense, heterogeneous urban fabric covering an area of 15.30 ha of which 11.00 ha are built-up. It is composed of 20 irregularly-shaped blocks, with each block comprising 4 to 32 houses, forming a total of 80 houses. The very urban fabric of the Ksar is a testament to the skill of its builders. Moreover, the architecture and the gradual development of the Ksar are intertwined with the history and geography of the region. This is due to the fact that the location of the Ksar on the pilgrimage caravan routes and its natural beauty contributed to making it a place of cultural and knowledge
exchange. As for the surrounding area, the oases established on the southern edge of the Aurès in these narrow gorges where the rivers of the Saharan slope have created passages, certainly existed from antiquity (Gsell, 1911; SADC, 1916). The presence of bazinas that were used to collect and store water for agriculture and human consumption in arid regions, and the discovery of snail pits, dated between 4,000 and 9,000 years BC, in the area are evidence of the ancient civilizations that existed around Khanguet Sidi Nadji well before the arrival of Sidi Lembarek Ben Kacem who founded the Ksar in 1602 (Figure 04).

As for Ksar Khanguet Sidi Nadji itself, it has a defensive wall made of rammed earth, forming a thick and robust rampart that rises from 3.50 to 7.60 m high at its main gate (Nasri, 2007; Makhloufi, 2010). The typical houses of the Ksar have a compact and closed structure with an average living area of 180 to 260 m². They are built of mud bricks, rising to a height of 7 to 8 m, and are distinguished by their organization around a central space, where daily activities take place. Spaces are hierarchical, ranging from communal to individual ones, passing through the covered courtyard. The latter is the central space giving access to all rooms. This configuration is motivated by several constraints, including maximizing the use of living space, better protection against weather, and effective natural ventilation. As for the public spaces of Ksar Khanguet Sidi Nadji, they consist of two mosques, a public square, serving also as a market, and palm groves. The Ksar also has other typical structures of ksour, such as shops, and even a barracks. Moreover, modern day structures exist such as a pharmacy, a reservoir, a primary school, and a playground. As for the passages within Ksar Khanguet Sidi Nadji, they are formed by narrow streets and alleys, generally inaccessible to current means of transportation, except for the altered parts of the Ksar, introduced in the French and Independence eras, which are equipped with streets with larger dimensions. The original alleys form covered passages, which have been designed to offer shaded spaces and cool stops throughout the Ksar. What distinguishes Ksar Khanguet Sidi Nadji from the majority of other ksour in the Sahara is the presence of a second story for a large number of houses. This demonstrates a mastery of construction techniques with perfect adaptation to the morphology of the sloping terrain. However, the current state of the Ksar, with its rough and irregular surface punctuated by cracks and crevices, testifies to the wear and tear of time and weather.

El Hocine El Wartilani, the renowned 17th-century traveler, also mentioned Ksar Khanguet Sidi Nadji and described it as a holy place after he visited its Zawiya Nasiria. The latter was a very famous Islamic community center and one of a kind in Algeria. From all parts, students came to it to seek knowledge, and the governing authorities of the time wanted to subsidize it after having noticed the services it rendered in education and training of scholars. Youssef Ben Mustapha El Turki, the dey of Tunis, gave Zawiya Nasiria the investiture of the command over Ksar Khanguet Sidi Nadji and its surroundings. It is for the continuation of this purpose that the Sidi Lembarek Mosque was built many years later in 1732 by Tunisian masons (Abbas, 2004). There is also the large seraglio named Ksar Lehsainia built in 1679 following the Ottoman architectural style for castles and palaces, with its rich ornamentation featuring
decorative motifs in raw earth brick (Figure 05). The serglio exceeding 12 m in height consists of three stories as well as a garden. Ksar Lehsainia was an important place culturally and socially, where people gathered to solve daily problems and study thanks to its library. The French presence slightly altered the original urban fabric by introducing new structures such as the municipal center and the prison. These structures are still located in the northern part of the urban fabric and were used for military purposes at that time (Nasri, 2007; Makhloufi, 2010).

When it comes to delving into the history of the Ksar, it’s worth mentioning the museum located in the heart of its ancient core (Figure 06). Housed in a repurposed existing structure, the museum’s exhibits display a fascinating collection of the local heritage. The collection is made possible by donations from the families that resided in the Ksar, and it includes historical manuscripts (Figure 07) and everyday tools and weapons spanning from the Ksar’s foundation to the time of the Algerian Revolution (Figure 08). Among the exhibits are also texts and copies of manuscripts that give accounts of the founding of Ksar Khanguet Sidi Nadji and its history. According to these texts, the choice of the site for establishing the Ksar was based on a local chronicle that was famous in the region. The chronicle states that Lembarek Ben Kacem, a pious man, saw his grandfather Sidi Nadji in a dream, where he told him to settle in the region in question, a place of grace. Lembarek Ben Kacem headed towards the region and settled permanently, with the help of his companions, and founded a mosque and some settlements around it, which became the core of the village. He also named the village after his grandfather as a sign of respect.

Ksar Khanguet Sidi Nadji is an impressive example of earthen architecture that showcases the beauty and durability of natural materials. Built using locally sourced earth and natural materials in the challenging conditions of the Sahara, its remains stand as a testament to the skill and ingenuity of its builders. The next section gives more details about earthen architecture.

3. Earthen Architecture

For centuries, earth has been a widely used building material in architecture due to its abundance and accessibility (Houben and Guillaud, 1994; Mileto and Vegas, 2018). Its composition gives rise to a diverse range of color, texture, and granularity. In this regard, natural resources like earth, sand, and clay are used in earthen architecture to construct a wide range of structures. These include common buildings like homes, schools, and markets, as well as monumental structures like the Great Mosque of Djenné in Mali, the Taos Pueblo in New Mexico, USA, and the rammed earth walls of the Hakka people in China, among many others. Despite the prevalence of modern building materials like concrete and steel, and due to its interesting properties, earthen architecture is regaining popularity as a cost-effective, eco-friendly, and sustainable option for construction (MOOCBD).
Earthen architecture encompasses a wide range of architectural styles that reflect the various techniques and methods used in different cultures (Houben and Guillaud, 1994; Mileto and Vegas, 2018). In the 1980s, the research team CRATerre identified 12 main techniques and methods for working with earth, namely digging, covering, filling, cutting, compacting, shaping, stacking, molding, extruding, pouring, forming, and applying (Figure 09). Recent research has been conducted to enumerate all the variations and subcategories of the techniques and methods used around the World, resulting in an even greater understanding and appreciation of the diverse architectural styles that are possible with earthen architecture. For instance, the Terra Europae project was launched to study earthen architecture in European Union countries (Correia et al., 2011). In the same way, the following examples from the Algerian context illustrate a similar reasoning:

- **Construction by removal** (caves and excavations), such as the Ghoufi Canyon and some parts of Ksar Khanguet Sidi Nadji (at the foothills of the Aurès Mountains), which involves excavating the natural land to create architectural vaulted spaces that are built underground or externally due to their nature.

- **Monolithic construction** (cob, piled earth, rammed earth, etc.), in places such as Taghit, which involves piling earth directly on the site to build walls. A formwork can be used for consolidation purposes. Other materials like stone, brick, lime, and gypsum can be added to the mix. Next, the composite is tamped by layers inside the formwork, or in layers stacked manually, smoothed, and cut at a later stage.

- **Construction by pieces** (clod, adobe, sod, cut earthen blocks, compressed earth blocks, etc.), such as the Kasbah of Algiers, which involves preparing bonding pieces that may have been air-dried earlier (adobe) or executed while still damp (clod). The earth is then manually modeled or shaped with a wooden mold in different ways, cut into blocks, then combined with different bonds, and used in the walls or even for the construction of vaults.

For the particular context of Ksar Khanget Sidi Nadji, which generally follows what is found in the ksour of the Algerian Sahara, the construction process of the houses can be described as follows:

- To create the foundations, the builders first excavated the ground to approximately 0.40 m deep, until obtaining a rocky soil more suitable for construction. They then directly anchored the foundations into the rock. These were made of natural stone, generally extracted from Oued El Arab, which is adjacent to the Ksar site. The natural stone used, with a width ranging from 0.50 to 0.70 m, was either left in its raw state or manually shaped (Nasri, 2007; Makhloufi, 2010). The motivation behind its use comes from its solidity as well as its resistance to water infiltration. This explains its use in other parts of the houses, including the walls of the substructure, some load-bearing walls of two-story houses, and possibly for fencing purposes.

- For the installation of load-bearing walls, the builders used sun-dried clay bricks with dimensions of approximately 0.15 m × 0.12 m × 0.30 m. The bonding mortar used was made of the same material.
as the brick. For waterproofing, two different materials were used: lime for coating the interior walls, and clay for coating the exterior walls. Following this process, it is possible to obtain walls up to 0.40 to 0.80 m thick. The process described here corresponds in CRATerre’s classification to cutting and molding techniques. The process used for building the load-bearing walls has the advantage of providing very relevant thermal qualities to the context of Saharan houses. Not only do the clay bricks serve as thermal insulation due to their significant dimensions, but the walls themselves ensure that the heat accumulated during the day continues late into the night. Consequently, the houses thus built are generally warm in winter and cool in summer.

- For the roof, the builders opted for wood and palm trunks (Figure 10). Like the majority of constructions in the south, weak points and wear areas such as corners and openings were made from wooden trunks. Due to its insulation and waterproofing qualities, clay was used to create the finishing layer for flat roofs. This corresponds to the covering technique according to CRATerre’s classification.

Understanding the characterization of earth is an important task that allows for various activities such as choosing a building site, assessing construction materials, performing diagnosis, and planning appropriate interventions (MOOCBD). To achieve this, three types of tests can be used: field tests, laboratory tests, and on-site tests. These tests complement each other to provide a detailed characterization of the building material (Guillaud, 2007). Field tests, mainly organoleptic assays based on the senses, such as touch and sight, inform us about the texture, consistency, and grain proportions that can be estimated by touching the earth. The second type of test, laboratory tests, offer specific characterization of the earth and allow for the evaluation of the performance of the finished material. These tests are time-consuming and are based on quantitative measurements obtained with specialized equipment, producing indicators such as mass, length, features obtained for X-ray imagery, mineralogy indicators, and chemical properties. For example, the proportions of grains according to their size can be determined by sieving the earth. Finally, the third type of test is done on-site and is frequently used by professionals to characterize the finished material under real conditions. Decisions are then made according to the obtained results. For example, drying, homogeneity, and other similar indicators are analyzed on-site. Additionally, tests performed on a wall provide many useful parameters for the reformulation of the building material, the overall performance of the resulting structure, and its aesthetics.

Earthen architecture has a rich cultural and artistic heritage, and its impact extends beyond the purely functional and engineering aspects of architecture and construction (Houben and Guillaud, 1994; Mileto and Vegas, 2018). Throughout history, earthen buildings have played a significant role in shaping the identity and character of different societies, reflecting their values, beliefs, and way of life. Earthen architecture is often associated with vernacular building traditions, which are based on local materials,
techniques, and knowledge, reflecting the cultural and environmental context of a place. As such, earthen buildings are an essential part of the cultural heritage of many communities, representing their history, craftsmanship, and identity. Additionally, earthen architecture can contribute to social cohesion and community engagement by involving local communities in the construction process and providing opportunities for skill-building, employment, and empowerment.

Earthen architecture, celebrated for its sustainability and aesthetic appeal, faces challenges in desert and Saharan regions, making it less viable for residents. Technically, erosion and weathering can weaken earthen structures, particularly in areas with heavy rainfall or high winds. Water damage, including from rising salty water, can cause dampness, cracking, and stains. Fire is also a risk due to low heat resistance materials like wood, straw, palm, and grass, as well as gaps in the structure. Climate change puts earthen structures at greater risk of damage from flooding and extreme temperatures, compromising their structural integrity. Earthquakes and other natural disasters also pose risks. Socio-economically, earthen architecture may be seen as a symbol of poverty or underdevelopment, and modern amenities may be preferred. Urbanization and migration to urban areas have led to a decline in traditional building practices and skilled craftsmen. In this regard, the next section provides more details on how the aforementioned factors play in the context of Ksar Khanguet Sidi Nadji.

4. Assessment Of Ksar Khanguet Sidi Nadji

Ksar Khanguet Sidi Nadji, a historic site of great cultural significance, is suffering from extensive deterioration (Nasri, 2007; Makhloufi, 2010). The Ksar was completely abandoned by its residents leaving it unattended for. The damage is evident in the houses, its other structures, and alleys. The houses, which have sustained damage to their foundations, walls, roofs, and coverings, are in urgent need of masonry work. While the foundations are still relatively solid, water infiltration over time has weakened them. For the majority of the houses, the exterior walls are generally still standing, but internal walls are in a precarious state. Roofs made of palms are rotten and in a state of degradation, and the coverings need to be redone (Figure 11). The same goes for the alleys which are filled with detritus and ruined material (Figure 12). This situation not only reduces the aesthetics of the site but also poses health and hygiene risks for both residents and visitors.

Ksar Khanguet Sidi Nadji, like many earthen architectural sites around the world, has been affected by an array of factors such as socio-economic shifts, industrialization, lack of legislation, ignorance, neglect, and even indifference. As its residents, mostly farmers, were forced to diversify their activities, the traditional earthen architecture and its building skills, once symbols of prestige, were increasingly stigmatized as a sign of poverty. Moreover, the use of modern means of transportation and machinery exposed the Ksar to vibrations from adjacent road traffic and daily activities, adding to its structural damage. The ill-planned introduction of new elements, such as electricity poles, street lamps, and modern
structures, contributed more and more to the disruption of the traditional urban fabric of the Ksar, adding to the disruption initiated in the French era. Also, the understandable desire by the residents for more modern and comfortable living spaces led them to adopt new construction techniques and materials, which interrupted the homogeneity of the houses and resulted in the coexistence of old and new architectural features that strongly contrast in their morphology, structural properties, and aesthetics. Additionally, the phenomenon of abandonment, resulting from the lack of employment and sources of revenue and the search for a better living environment, is also prevalent and has ultimately contributed to the neglect and deterioration of Ksar Khanguet Sidi Nadji.

Natural factors have also played a significant role in the deterioration of Ksar Khanguet Sidi Nadji, given the inherent susceptibility of earthen architecture to such factors. The presence of important hydraulic sources, such as Oued El Arab and underground aquifers, has caused direct damage to the foundations and walls of the structures. The rise of capillary water, especially saltwater, is a typical example of the Saharan context. Climate effects, including rain, have aggravated moisture-related problems, causing water to penetrate the materials and increase the level of underground aquifers and Oued El Arab mentioned earlier. Also, this have caused both flooding and erosion, damaging homes, infrastructure, and agriculture (Khentouche, 2021). Erosion had lead to changes in the river's course, loss of fertile soil, and damage to nearby structures. Continued monitoring and investment are necessary to protect the region's communities, agriculture, and infrastructure from these hazards. Rain has also caused direct mechanical damage by violently striking the surface of the structures (Nasri, 2007; Makhloufi, 2010). Similarly, freezing and thawing of water molecules, particularly saltwater, has caused cracks in the materials, especially where the thickness is minimal. Strong winds have created pressure forces on the exposed faces and suction on the opposite faces of the structures. Additionally, they have caused structural vibrations by resonance, transport of solid particles impacting the facades, and rapid evaporation of water contained in the external layers of the walls, which has further accelerated the crystallization of salts. Also, the degradation caused by microscopic organisms, insects, mammals, birds, and plants has contributed to the damage suffered by the Ksar. This is mainly due to the fact that most of the houses in the Ksar are equipped with a space reserved for animal husbandry. Finally, time has also contributed to the deterioration of Ksar since the gradual mechanical action of gravity is known for its tendency to flatten the elevations of man-made structures.

Having assessed the current state of Ksar Khanguet Sidi Nadji, the next step is to address the restoration of this historical site. The next section outlines the proposed restoration plan and highlight the key challenges that need to be addressed to ensure its successful implementation.

5. Restoration Of Ksar Khanguet Sidi Nadji
In light of what we have previously outlined, it is clear that the restoration of Ksar Khanguet Sidi Nadji is a necessity, whether it be for preserving its historical heritage, helping residents return to their homes, or for the region itself from an economic standpoint, for the exploitation of oases and even tourism. To this end, we propose implementing a restoration protocol targeting the damaged houses of the Ksar, using locally sourced earth-based materials for the houses to make them habitable again. Furthermore, we envision consolidating this effort by undertaking rehabilitation actions on these houses while respecting the specifics of the Ksar in terms of its architecture, heritage, and even the climatic and socio-economic factors of the region. It should be noted that structures other than houses are managed by the state, and their restoration falls within the framework of programs related to the management of monuments and public spaces. For instance, the seraglio was restored between 2002 and 2005 (Nasri, 2007; Makhloufi, 2010). The houses, on the other hand, are private properties. In this regard, the residents themselves have differing opinions on the direction to follow: rehabilitation or demolition and reconstruction. However, this does not prevent being proactive and proposing solutions, since there is a possibility of unlocking the situation, given that the Ksar is completely abandoned and there is a possibility of resolving this situation by implementing and enacting new educational, legislative, and financial mechanisms.

Regarding the proposed protocol itself, the proposed restoration approach is based on the anastylosis method. The latter is a restoration method used in archaeology to rebuild ancient structures using their own materials (ICOMOS, 1964). This method involves dismantling the damaged structure, sorting the materials, and reassembling them using the techniques used to build the damaged structure in the first place. The objective is to restore the appearance and functionality of the original structure while preserving its historical integrity as much as possible. The Venice Charter is a reference document for the conservation and restoration of historical monuments and sites. It sets out guiding principles for conservation interventions, including anastylosis. According to the Charter, anastylosis should only be considered in exceptional circumstances, when archaeological and historical evidence is sufficient to justify a reconstruction and when original materials can be identified and reused meaningfully. The Charter also emphasizes the importance of maintaining a clear distinction between the original elements and the restored parts to avoid any confusion about the authenticity of the structure. Drawing inspiration from these points, we propose for the specific context of Ksar Khanguet Sidi Nadji an approach that will allow for the production of new adobe and earth blocks that will be used as basic materials for repairs aimed at reconstituting the dilapidated parts, treating cracks, refurbishing coatings, and floor coverings. These new materials are to be used only if necessary. In other words, the original building materials composing the deteriorated structures are tested. Based on this, they are either properly returned to their original place or completely replaced.

On the complementary urban aspect, upgrading works are also mandatory. They will consist of equipping the Ksar with all the necessary amenities, including the installation of various water networks, burying of
electricity and gas networks, setting up Internet access, etc. Carrying out development and enhancement works, strengthening the houses of the Ksar and the infrastructure equipment and embellishing the environment and the outer edges of the site in terms of roads, streets and alleys, communication networks, water supply, sanitation, signage, etc. Also, setting up reception facilities such as sanitary blocks, indication panels, directional signs for the visiting circuits. In contrast to previous attempts to introduce modern amenities to the Ksar, our efforts are carefully planned to consider the historical, architectural, urban, social, and other characteristics of the Ksar, as well as the needs of its residents. Furthermore, our action plan can be extended to include the restoration of natural spaces, such as the oases present on the site, which will in turn contribute to the revival of agricultural and economic activities in the region. As a result, this initiative will serve as an incentive for the residents to return to the Ksar, further promoting its revitalization.

On the human aspect, the plan includes training in earth architecture for young architects and students so that they can acquire practical experience in the restoration of earth buildings. We also plan to have a participatory worksite that will allow the residents of the Ksar to participate in the restoration of their own houses while benefiting from expert guidance. This collaborative approach ensures that the cost of restoration will be minimal for the residents and encourages the adoption of sustainable construction practices in the future.

The following subsections give more details on the technical aspects of the proposed restoration protocol for the houses (Figure 13).

5.1. Preparation of Construction Materials

To cope with the site's specifics, we recommend the use of manual or motorized track wheelbarrows and shovels to transport raw materials. Indeed, the terrain is difficult to access and unstable, making the use of large transportation vehicles impossible. The dimensions and weight of the materials also require the use of appropriate tools. The advantages of using track wheelbarrows or shovels are numerous, including speed, maneuverability, and precision.

As for the process of preparation of construction materials itself, it consists of:

- Clearing and cleaning the intervention site of waste and debris making it accessible.
- Digging down to the foundation of the walls to analyze technical and structural damage and collect reusable materials if it is the case.
For material preparation, the collection of soil and debris is done manually or with a motorized track wheelbarrow and shovel. Collected debris containing various materials, such as cut earth bricks, stones, lime, and sand, are then sorted, sifted, ground, and reduced to a soft powder using a mechanical crusher. It is necessary to carry out soil identification using standard tests. Elemental chemical analyses should also be performed to determine the soil composition.

The dosing and mixing of the original components must respect the ideal proportions for a good quality adobe. In the Saharan ksour context, the proportions could be as follows: 55 to 75% of sand, 10 to 28% of silt, and 15 to 18% of clay. It is also possible to add certain materials to the mixture such as stabilizers. This process is to be performed multiple times to test different formulations and obtain high-quality technical performance.

The cut earth bricks are then shaped and molded, and left to dry in the shade, away from the sun to prevent cracking and premature drying. The bricks are also tested to determine which formulation is most resistant to compression tests and to verify each cut earth brick before distribution on the construction site. At this specific point, it is possible to introduce certain modifications to the original raw material in order to improve it while remaining as faithful as possible to its original nature and regional specifics. This includes, among other things, adding cement and quicklime to improve durability and waterproofing properties (Zebair et al., 2019), as well as adding date palm fibers to the aforementioned mixture for certain cases (Guettatfi et al., 2023). As for the bricks on the exterior side of the walls, it is possible to add ornamentation made of cut earth bricks at the openings (Atelier Aïno et al., 2023). This approach has several advantages, including enhancing the hygrothermal performance of the bricks, which improves the regulation of moisture and heat transfer within the house. Additionally, the bricks will contribute to making the building more attractive and upping its overall aesthetics while highlighting the architectural details of the construction.

5.2. Intervention on Load-Bearing Walls

Once the foundations are excavated, we must proceed with thorough cleaning and dusting of the substructures. This step is crucial to facilitate the analysis and repair of damages, in order to effectively consolidate them. It is important to note that the foundations can rise above ground level, forming a plinth that can reach 1 m in height. This plinth has an essential role in construction, as it protects the habitat from rainwater runoff and reduces capillary rise problems (Idir, 2013).

For sub-basement walls, load-bearing walls, and interior walls, it may be necessary to partially dismantle and then carefully rebuild them. This operation will restore better cohesion of the structure as a whole, replace deteriorated elements with new, cut earth bricks, and eliminate tensile stresses. This solution is particularly suitable when the masonry is of very poor quality and has swelling or cracks (Figure 14).
To remedy stagnant water at the base of the structure, it is necessary to install a drain, which is a device that controls the moisture present at the foot of the wall. The system intercepts rainwater and prevents it from reaching the base of the walls, channeling it towards a network of rainwater drains. We also propose the technique of vegetative engineering as a prevention of erosion of the foundation stone of the houses near the riverbank. Vegetative engineering can be used by planting trees, shrubs, and other plants along the bank. These plants will act not only as anchors for the soil, preventing erosion due to water movement in Oued El Arab, but also to remedy the deterioration caused by strong winds experienced in Ksar Khanguet Sidi Nadji.

Lime grout is a highly durable construction material that can effectively adhere to the porous surfaces of masonry. It is made up of hydrated lime and water, and can also be enriched with additives to improve its properties. Before injecting the lime grout, it is important to prepare the surface of the masonry by removing dirt, dust, and debris. The voids and cavities in the masonry are then located and cleaned. Once the preparation is complete, the lime grout is injected into the voids using a pump specifically designed for this purpose. The lime grout is pushed under pressure into the voids and cavities, effectively filling all the hollow spaces (Figure 15). Once the lime grout is injected, it solidifies and binds with the bricks and surrounding masonry, creating a strong and durable bond. The lime grout must be of high quality, and the injected amount must be properly measured to avoid overloading the walls and weakening the masonry. The lime grout injection technique is a non-invasive in the sense that it does not require major work, such as creating new openings or installing external reinforcements. This technique is therefore particularly suitable for the renovation of historic buildings where the preservation of the historic appearance and architectural integrity are paramount.

Furthermore, to reinforce the load-bearing walls, we recommend the technique of chaining with earth bricks or timber. This technique is commonly used to reinforce existing walls or to improve the resistance of a newly erected earth brick wall. It involves adding a layer of additional pieces at regular intervals between the walls. The added pieces are placed perpendicular to the walls, so that they cross the earth brick joints, and are fixed to the walls using mortar. It is important to choose earth bricks that are the same size as those in the walls to be consolidated and strong enough to support the additional load of chaining. The earth bricks should be placed at regular intervals, usually every 0.60 to 0.90 m. Timber is another option for chaining, but the used beams must be thick and strong enough to support the additional load. They are fixed to the walls with steel studs or bolts. Overall, the chaining technique is a proven method for reinforcing earth brick walls, distributing loads over a larger surface area and preventing cracks from spreading. However, it is essential to ensure that the chaining is properly installed and strong enough to withstand the additional stresses.
5.3. Openings, Coverings, and Roofs

Regarding the opening elements, it is imperative to replace the wooden or stone lintels that are rotten or damaged. However, this operation is delicate and requires significant shoring work to ensure the safety of workers and the stability of the structure. It is important to consider the damage affecting the openings of a building in order to develop an effective strategy for repairing and protecting them. Damage can come from a poor base on which the openings rest, or the presence of obsolete materials such as rotten wood. To treat the carpentry, it is important to follow two steps: repairing the support and applying paint. First, the wood must be brushed and cleaned before applying insecticide to eliminate harmful insects. This step must be repeated several times to ensure an effective result. Then, the carpentry must be painted protecting it against insects and moisture. It is important not to use varnish as it does not allow the wood to breathe. If a diagnosis reveals a pathology at the level of the lintel, such as wood rot, it is necessary to replace the lintel in question. In this case, the following steps should be followed: shoring up the masonry above the lintel, removing a few courses above the lintel, removing the deteriorated lintel, preparing a stronger and larger wooden lintel, carefully installing the new lintel, connecting the supports with lime mortar, and rebuilding the dismantled brick courses.

As for the roofs and coverings, the first step would be to rebuild the collapsed walls to reach the level of the roofs. Depending on the encountered situation, it may be necessary to replace the damaged palm trunks and reproduce the finish layer of flat roofs. In the context of the Ksar, the roofs often take the form of terraces. Although terraces receive most of the solar radiation, their composition assures thermal insulation thanks to a structure made of palm tree trunks. These trunks measure between 2.0 and 2.5 m in length, and are supported at their ends. This layer is then covered with a bed of palm leaves to prevent water leaks. A thick layer of earth is then added to consolidate the whole, this layer having a thickness of 0.10 to 0.15 m (Figure 16). The whole is then protected by a layer of white lime mortar waterproofing. It should be noted that this terrace roofing technique is particularly suitable for hot climate regions, where access to natural ventilation is essential to maintain a comfortable temperature inside the house. The materials used in this technique are also locally available, making them economical, environmentally friendly, and faithful to the vernacular aspect of the region.

The restoration plan for Ksar Khanguet Sidi Nadji has been outlined, setting the stage for future research and exploration of this historical site. In the concluding section of this article, we will summarize our proposed protocol and discuss the broader applications of our approach.

6. Conclusion

Preserving heritage sites is not just about preserving the physical structures, but also about maintaining collective identity and ensuring sustainability for future generations. One such example is Ksar Khanguet
Sidi Nadji, located in the Algerian Sahara, with its rich history and unique earthen architecture. However, the current state of the Ksar is a cause for concern, with its structures and alleys deteriorating, and houses abandoned by its residents. This dire situation is the result of various factors, including challenges related to earthen architecture, natural phenomena, and socio-economic considerations. The state of the Ksar not only poses a threat to its cultural and architectural heritage but also to the well-being of its residents and visitors.

In response to this pressing issue, we have proposed a comprehensive restoration protocol that focuses on the site itself and its residents. Our approach includes meticulous repairs to the foundations, walls, openings, and other affected areas, utilizing original materials found on-site whenever possible. Taking inspiration from the anastylosis method used in archaeology, our aim is to preserve the original nature and aesthetics of the Ksar. Introduction of new elements will be limited and carefully controlled, adhering to mandatory tests and aesthetic constraints. We recognize the importance of making Ksar Khanguet Sidi Nadji viable again for its residents, and to achieve that, we have proposed the installation of necessary amenities such as water, gas, and electricity networks, sanitary blocs, and indication panels. As the Ksar is adjacent to Oued El Arab, we have also suggested utilizing vegetative engineering by planting trees, shrubs, and other plants along the riverbank to anchor the soil, reduce erosion, and protect against strong winds. But our vision goes beyond the physical restoration of the Ksar. We believe in empowering the local community and building capacity for sustainable heritage preservation. As part of our proposal, we have outlined plans to provide training in earthen architecture for young architects and students, allowing them to gain practical experience in building restoration using earth-based materials. We also plan to implement a participatory construction site that engages the residents in the restoration of their own houses, with expert guidance.

We strongly believe that our proposals for the preservation and promotion of the cultural and architectural heritage of Ksar Khanguet Sidi Nadji are actionable and feasible. However, they need to be integrated into a broader vision that involves various stakeholders, including the residents of the Ksar, artisans, researchers, specialists, policymakers, and governing bodies. Organizing conferences, seminars, workshops, and technical sessions would be a good starting point for implementing such a plan. In parallel, we propose creating a detailed digital inventory of the heritage using technical surveys, photos, and videos, regularly updated and made accessible to all. We also suggest using 3D virtual representation to bring the site to life, and implementing heritage mediation activities such as guided tours and cultural events. Additionally, we recommend creating an atlas of the Algerian ksour, with an interactive map showcasing the diversity of cultural and natural sites, allowing them to be connected by a tourism itineraries. To provide an organized framework for preservation and restoration efforts, we recommend establishing an ecomuseum. An ecomuseum is a museum that conserves and promotes the cultural heritage of a region by involving the local community. For Ksar Khanguet Sidi Nadji, an
ecomuseum can help with heritage conservation, cultural mediation, community participation, training, and advocacy for heritage preservation to the involved actors.

In conclusion, the preservation and promotion of the cultural and architectural heritage of Ksar Khanguet Sidi Nadji require a comprehensive approach that includes physical restoration, community engagement, stakeholder involvement, heritage mediation, and sustainable management practices. By integrating these components into a broader vision and involving various stakeholders, we can ensure the long-term sustainability of the site and safeguard its cultural and architectural heritage for future generations.

References


Figures
Figure 1

The seraglio of Ksar Khanguet Sidi Nadji (Taken in March 2019).
Figure 2

Overview of Ksar Khanguet Sidi Nadji at the foothills of the Aurès Mountains (Taken in March 2019).
Figure 3

Satellite view of Ksar Khanguet Sidi Nadji (Captured using Google Earth in April 2023).

Figure 4
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**Figure 5**

Ornamentation visible on the outer walls of the seraglio of Ksar Khanguet Sidi Nadji (Taken in March 2019).

**Figure 6**
The local museum of Ksar Khanguet Sidi Nadji (Taken in March 2019).

Figure 7

Rare historical manuscripts on display at the local museum of Ksar Khanguet Sidi Nadji (Taken in March 2019).

Figure 8

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Flowchart illustrating the process of preparing construction materials by recycling the debris present at Ksar Khanguet Sidi Nadji.

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Flowchart illustrating the process of rebuilding a typical deteriorated load-bearing wall in the context of the houses of Ksar Khanguet Sidi Nadji.
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Flowchart illustrating the process of reinforcement through injection of a typical wall in the context of the houses of Ksar Khanguet Sidi Nadji.

Figure 16

Flowchart illustrating the process for repairing a typical roof in the context of the houses of Ksar Khanguet Sidi Nadji.