

Soluble Salt Migration in the Composite Masonry of the Ming Dynasty Kangling Tomb, the Ming Tombs, Beijing

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Abstract

The Ming Dynasty Kangling Tomb, one of the Ming Tombs in Beijing, exhibits notable salt weathering phenomena on the stone–brick composite structures of its Ming Tower (Minglou). Field observations reveal visible efflorescence, granular disintegration, and color changes along the lower stone courses and arch bases. This study investigates the migration and accumulation of soluble salts within different masonry materials and interfaces.

A combination of surface mapping, photographic documentation, and Literature search was conducted to identify the patterns and mechanisms of salt transport. The results show that salt accumulation is concentrated at the junctions between the dense limestone blocks and porous grey bricks, where moisture movement and evaporation gradients are most pronounced. The observed white crusts and blackened damp areas suggest alternating cycles of capillary rise, evaporation, and recrystallization.

These findings indicate that the heterogeneous nature of the masonry – particularly the contrast in porosity and permeability between stone and brick – plays a crucial role in directing salt migration. The study provides insights into the deterioration processes of composite heritage structures and highlights the importance of moisture and salt management in conservation planning for the Ming Tombs.

Keywords

salt weathering, Ming Dynasty Kangling Tomb, the Ming Tombs, soluble salts, composite masonry

1 Introduction

Salt weathering is widely recognized as one of the major deterioration processes affecting historic masonry structures. The interaction between moisture and soluble salts can lead to a range of decay phenomena, including efflorescence, surface crust formation, granular disintegration, and material loss. These processes are particularly critical in monumental heritage sites, where long-term exposure to environmental conditions promotes repeated cycles of salt dissolution, transport, and crystallization [1–3]. The migration of salts along material interfaces and within mortar-filled voids exacerbates damage, especially in traditional brickwork such as five-faced dressed and shoulder-faced brick constructions [4, 5].

From the perspective of the research object, the Ming Dynasty Kangling Tomb, as part of the Ming imperial burial complex, exhibits a distinctive structural configuration. The Square City consists of a brick masonry structure built upon a stone Xumizuo, forming a composite system of different materials.

Salt weathering processes in such a composite masonry system have not yet been systematically investigated.

At the Ming Dynasty Kangling Tomb's Square City (a large rectangular stone structure) and Ming Tower (one storey red brick building), visible salt-related deterioration phenomena have been observed in situ, including efflorescence, mineral deposits, and surface degradation. These features are predominantly concentrated in the lower zones of the structure, particularly near the interface between the brick masonry and the stone pedestal. Despite their clear presence and spatial regularity, these deterioration patterns have not been systematically investigated, especially in terms of their distribution and underlying transport mechanisms.

This study aims to investigate the migration and crystallization of soluble salts within the composite masonry of the Ming Dynasty Kangling Tomb's Ming Tower, with a particular focus on the role of material interfaces and structural continuity in directing moisture and salt

transport. The research is based on field observation, mapping, and analysis of deterioration patterns.

2 Materials site and architectural background

2.1 Background of Ming Dynasty Kangling Tomb and Square City & Ming Tower

2.1.1 Ming Dynasty Kangling Tomb

As one of the components of the Ming Tombs, Ming Dynasty Kangling Tomb is also a world cultural heritage of Imperial Tombs of the Ming and Qing Dynasties (in 2000, the Ming and Qing imperial tombs were registered as a world cultural heritage for the first time, and in 2003, Ming Dynasty Kangling Tomb was added to the category of world cultural heritage as a part of the Ming and Qing imperial tombs).

Ming Dynasty Kangling Tomb is located in the Ming Tombs District, Changping District, Beijing, People's Republic of China (Fig. 1).

The overall layout of Ming Tombs follows a strict central axis ritual order, and each tomb takes Shendao (The Sacred Way) as the axis, and arranges ceremonial buildings and core sacrificial spaces from south to north.

Ming Dynasty Kangling Tomb is the joint burial tomb of Zhu Houzhao, the tenth emperor of the Ming Dynasty, and

his Empress Xia (Empress Xiaojingyi of Ming Wuzong), located at the eastern foot of Ming Dynasty Jinling Tomb (Lianhua Mountain) in the Tianshou Mountain Tomb District (northwest of the entire tomb area) (Fig. 2) [6, 7]. The tomb was built on April 30, 1521 (April 30, 1521), and the underground palace was completed in September of the same year, and the emperor's body was placed in it on September 22. In June of the first year of Jiajing (June 1522), the cemetery was completed, and it took one year.

Ming Dynasty Kangling Tomb covers an area of about 27,000 m², and the overall layout of the tomb building follows the previous system, in the shape of a front and back circle. The first courtyard is the tomb gate of the Ling'en Gate (now only the ruins remain), and the Ling'en Hall (now only the ruins), the left and right-side halls and the divine silk furnace (now no longer exist) are built. The second courtyard has three glazed doors as the front door, and there are Lingxing Gate and stone offerings inside. Behind the square courtyard is the Square City, Ming Tower and the place where the emperor was buried (Fig. 3).

In 1998, Ming Tombs Special Zone Office carried out closed protection of Ming Dynasty Kangling Tomb and repaired the collapsed tomb wall of Ming Dynasty Kangling Tomb [8]. On April 15, 2003, the Office of Ming Tombs Special Zone carried out emergency repairs on Ming Dynasty Kangling Tomb, which was completed in 2006. Its main repair projects include the repair of the roof of Ming Tower, the repair and reinforcement of the walls of Square City, the restoration of the glazed wall, the rectification of the Square City countertop and the bridleway, the reinforcement of the tomb wall, the repair of the three glazed gates, the protection of the ruins of the Ling'en Hall, and the dredging of the drainage system [9].



Fig. 1 Geographical location of the Ming Tombs (Source: Drawn by the author)

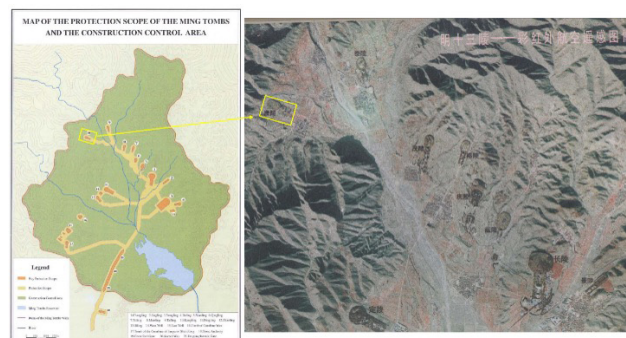


Fig. 2 Map of the Protection Scope of the Ming Tombs and the Location of Ming Dynasty Kangling Tomb (Source: Redrawn and adapted by the author based on [6, 7])

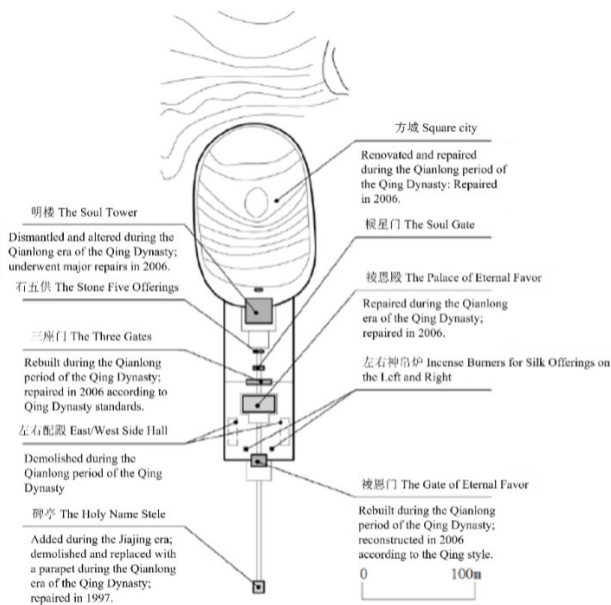


Fig. 3 General plan of Ming Dynasty Kangling Tomb (Redrawn by the author based on [8])

2.1.2 Square City & Ming Tower

Square City & Ming Tower is located at the end of the tomb axis and is an important monumental ground building that marks the location of the underground tomb (Xuanguo), which has both spatial dominance and ceremonial symbolism. It elevates the main body through the high platform and the Xumizuo, strengthening the monumentality and hierarchical order of the building.

In terms of structure, the Ming Tower adopts a composite masonry system based on masonry: the Square City's wall is built on the stone foundation of the Xumizuo, and there is a combination of different masonry methods in the brick part. The composite use of this masonry material makes the structure have significant differences in physical properties, pore characteristics and hygroscopic behavior.

At the same time, as the transitional interface between the building and the surface environment, the Xumizuo has long been affected by soil moisture, rainfall and dry-wet cycles, and has become a key area for the interaction between water intrusion and materials. This structural feature provides important conditions for water migration and enrichment of soluble salts.

As an important part of the Ming Tombs, Ming Dynasty Kangling Tomb's Ming Tower not only has historical and artistic value, but also provides a typical case for studying the environmental role and deterioration mechanism in traditional architecture.

2.1.3 Structure of Square City & Ming Tower

The overall structure of Square City & Ming Tower is composed of Ming Tower (Minglou) and Square City (Square City) from top to bottom and falls on the lower Xumizuo (Fig. 4).

Square City & Ming Tower is the core building of the Ming Dynasty emperor's tomb, and the shape originated from the Ming Emperor's Tombs in Fengyang, Anhui Province. For the first time, the Ming Dynasty Xiaoling Tomb added a single Square City & Ming Tower in front of the treasure city (Bao Cheng), which was inherited by the Ming Tombs. At the end of the Ming Dynasty, Li Zicheng's rebel army burned down the Ming Dynasty Kangling Tomb's Ming Tower (March 15, 1644) in Ming Tombs of the Ming Dynasty, and the "Imperial Tomb Illustrated Commentary" described it as "the remaining flames, the broken tiles and the collapsed walls, and the four walls of the urn door" [10]. In the fiftieth year of Qianlong, the Qing court overhauled Ming Tombs, and the Ming Dynasty Kangling Tomb's Ming Tower was completely rebuilt, and the volume was reduced after the reconstruction. During the Republic of China, according to the investigation of the 24th year of the Republic of China, most of the eaves of the Ming Dynasty Kangling Tomb's Ming Tower fell off [11].

The Square City & Ming Tower is composed of the lower square platform and the upper Ming Tower. In the 50th year of Qianlong, after a major overhaul by the Qing court, the structure of the Ming Dynasty Kangling Tomb's Ming Tower was changed to walls and ceiling are integrated., and the under Square City was also blocked [12]. After the founding of New China, Ming Dynasty Kangling Tomb and others were protected and repaired, and at the beginning of this century, in line with the principle of "repairing the old as the old", it was basically completed, and the Square



Fig. 4 Schematic diagram of the overall structure of Square City & Ming Tower and Xumizuo (Source: drawn by the author)

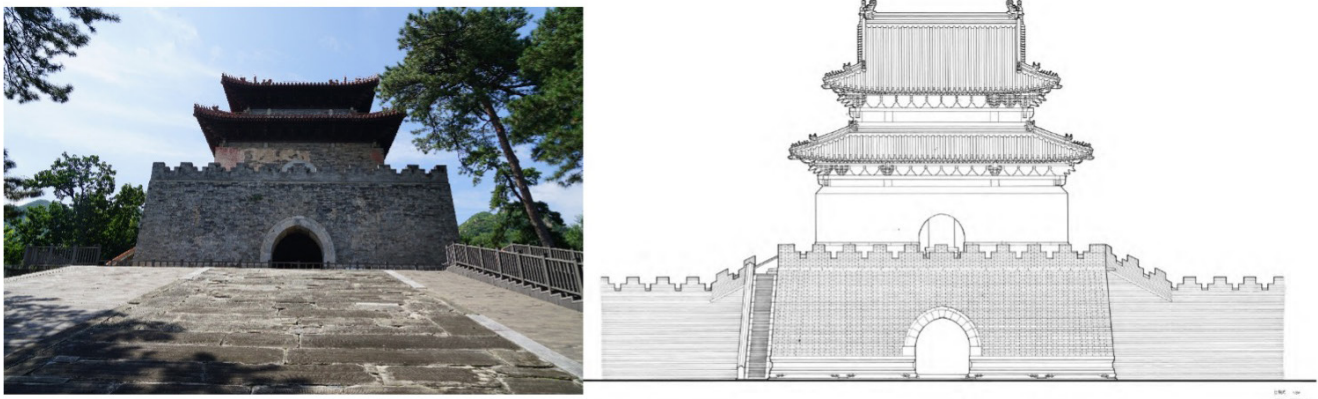


Fig. 5 Current situation of Square City & Ming Tower, Ming Dynasty Kangling Tomb (Source: Adopted by the author base on surveying and mapping of the School of Architecture, Tianjin University and photo taken by author)

City cave reappeared. Today, Ming Dynasty Kangling Tomb's Square City is a solid square city platform built of brick and stone, and the vaulted cave under Square City can lead to the treasure city. However, because Square City was blocked in the 50th year of Qianlong, Ming Dynasty Kangling Tomb's Square City still retained the outer pedal path for the tomb visitors to climb the city (Fig. 5). Its masonry method was originally a "dry swing to top" [13] masonry method, which did not apply mortar to the brick joints on the façade. This masonry method is applied to clay bricks, called "five-face dressed" bricks [13] (Fig. 6), five of the six faces of the brick are processed, and the brick is covered with ash (mortar is reserved to fill the gaps), as shown in the figure, the dotted line position is to reserve mortar to fill the gaps. After the renovation in 2006, under the guidance of the official "repair the old as the old", the masonry of the upper part of Square City (above the ticket) still adopts the same brick type and masonry method as the lower part (as shown in Fig. 7).

Ming Tower is located on the top of Square City and is a stele pavilion building on the top of the mountain. Its main

structure has undergone the evolution from wooden structure to masonry imitation wood structure, in order to be strong and durable, the Ming Tower is mostly changed to masonry imitation wood structure. During the Qianlong period of the Qing Dynasty, when the Ming Ming Dynasty Kangling Tomb was restored, the walls and the vaulted were built together to enhance the solidity. In addition, because the construction form and construction technology of the Ming Tombs are in the same vein, referring to the construction method of Square City & Ming Tower of Tailing (closest to the time of Ming Dynasty Kangling Tomb), Ming Dynasty Changling Tomb, and Ming Dynasty Xiaoling Tomb, these comparisons suggest a possible structural continuity between the Soul Tower walls and the Square City at Kangling; however, this arrangement remains to be verified through site-specific investigation.. According to archaeological research on the construction method of the Ming Dynasty Xiaoling Tomb's Square City & Ming Tower, the four walls of the Ming Tower were not simply built on the platform of the city, but began to build the wall from the inside of the Square City, and the wall of the Ming Tower was connected with the main part of the lower Square City platform [14]. This archaeological discovery is very important for the subsequent analysis of the causes of salt weathering in Ming Tower in Square City, Ming Dynasty Kangling Tomb.

As for the lower part of the Square City & Ming Tower, the Xumizuo, it first appeared in the Northern Wei Dynasty and became standard in the Ming and Qing dynasties, mostly used as pedestals for important palaces. The Xumizuo of the Ming Tower of Square City in Ming Dynasty Kangling Tomb is carved from white marble, and its basic composition (from bottom to top): Earthen base, Corner molding, Lower cyma molding, Waist section,

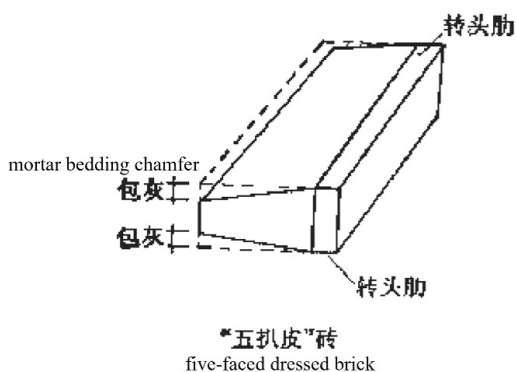


Fig. 6 Schematic diagram of five-faced dressed brick (Source: [13])

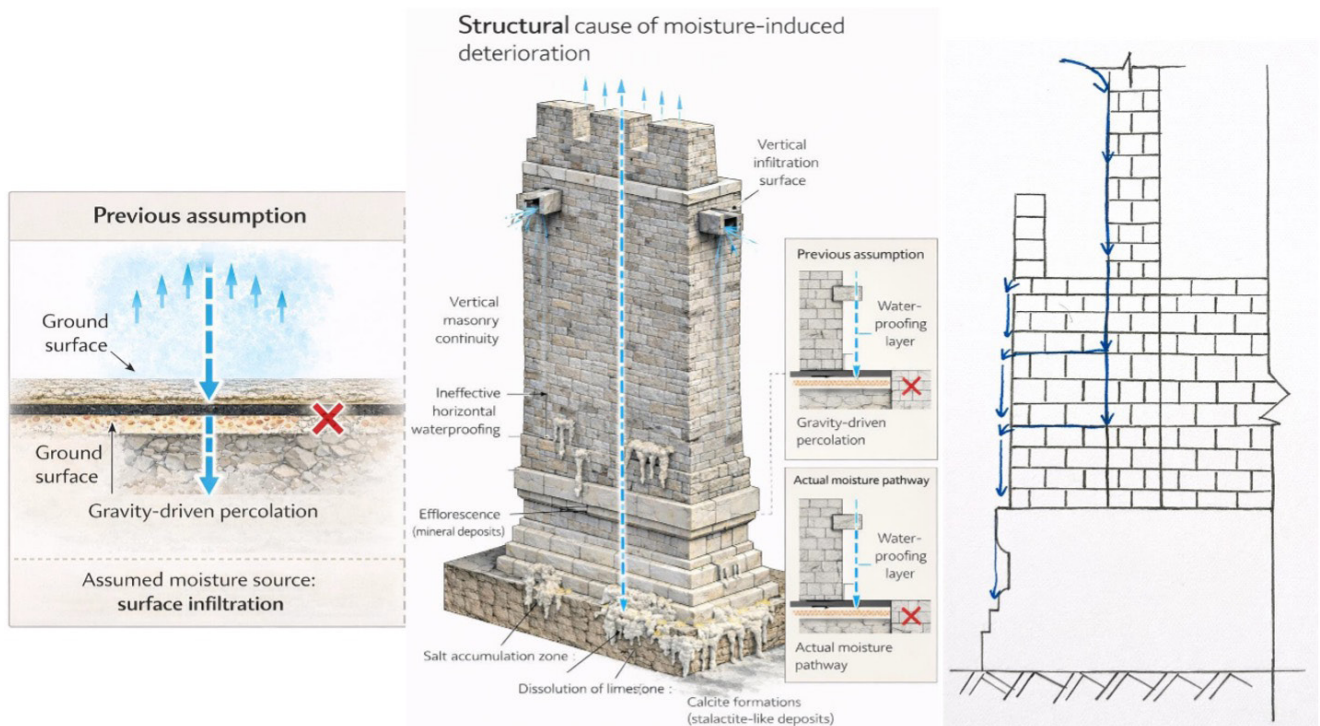


Fig. 7 Soluble salt movement routes (Source: Drawn by the author)

Upper cyma molding and Upper beam [13] (Fig. 8). The Xumizuo is connected to Square City as a load bearing structure.

3 Soluble salt movement phenomenon and analysis of Square City & Ming Tower

3.1 The movement of soluble salts in Square City & Ming Tower

Obvious weathering and pollution can be observed on the surface of the Ming Tower in Square City, Ming Dynasty Kangling Tomb (Fig. 9), and the diseases are mainly concentrated in the middle and lower part of the wall and the Xumizuo area.

As shown in the figure, the surface of the brick wall forms an obvious brick wall color difference line from the position of the vaulted. The lower brick shows light gray to grayish-white as a whole, forming a clear boundary with the darker brick wall in the upper part. In some areas, continuous white deposits can be seen adhering to the brick surface and the plaster joints used for repair, and some brick surfaces appear whitening.

There are obvious vertical flow marks on the surface of the wall, extending from the upper part of the brick wall down to the Xumizuo area, forming white strip-like traces. Some of the flow traces run through the brick wall and the stone Xumizuo, and the color deepens and sedimentary aggregation occurs at the turning point of the components.

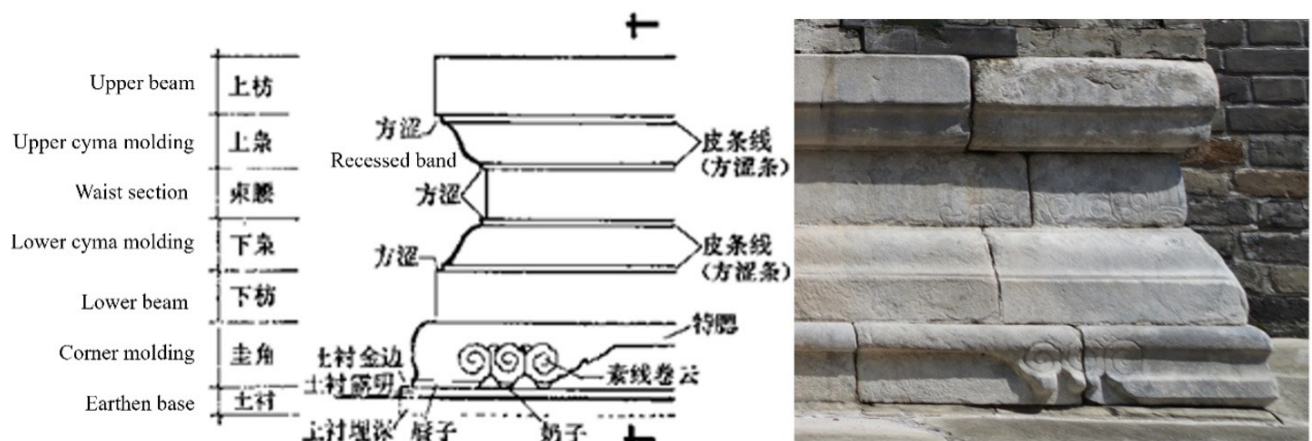


Fig. 8 Xumizuo structure (Source: Adopted by the author based on [13] and photo taken by author)



Fig. 9 Visible salt deposits and their spatial distribution on the Square City at the Ming Dynasty Kangling Tomb: (a) Overall view of the façade showing the affected areas; (b) Salt deposits and dark staining on the left-hand section of the Xumizuo and adjacent brickwork; (c) Salt deposits along the brick–stone interface and joints of the Xumizuo; (d) Distribution of salt deposits across the right-hand section of the Xumizuo and adjacent brickwork; (e) Close-up of dark staining and white deposits on the Xumizuo; (f) Close-up of white deposits along a vertical joint between stone blocks; (g) Close-up of white deposits on the brickwork and mortar joints; (h) Close-up of white deposits and dark streaks at the brick–stone interface. (Source: Photographs by the author.)

There are different degrees of material deterioration in brick masonry, including loose brick surface, edge damage, local loss and mortar degradation. The diseases in the lower brick wall area are relatively concentrated, and some brick surfaces have uneven weathering and hole-like defects.

Obvious pollution and deposition phenomena can be seen on the surface of the Xumizuo stone components, especially in the Waist section, Upper cyma molding and recessed band, there are continuous black flow marks and white attachments. The surface color of some areas is uneven, accompanied by local weathering and abrasion.

The overall disease has a strong regularity in spatial distribution, mainly developing along the vertical direction of the wall, and is more obvious in the masonry junction and the turning point of the components.

At Ming Dynasty Kangling Tomb, the observed distribution is characterized by three related features: a visible colour boundary near the level of the arched entrance, vertical streaks crossing the brick–stone junction, and

localized deposits on the waist, upper cyma molding, and recessed bands of the Xumizuo (Fig. 9). Together, these observations identify specific areas in which moisture movement and deposition may be linked. They provide a spatial basis for the subsequent interpretation, although the photographs alone do not establish the direction of internal moisture transport or the chemical composition of the deposits.

3.2 Analysis of the causes of soluble salt movement phenomenon in Square City & Ming Tower

The salt weathering disease in the Ming Tower of Square City in Ming Dynasty Kangling Tomb is not caused by a single factor, but by the complex deterioration process formed by the structure of the building structure, water migration path, masonry method, material characteristics and long-term environmental effects. From the field survey results, there is a clear correlation between the distribution of diseases and the building structure, especially in

the masonry junction area, the middle and lower part of the wall, and the turning point of the Xumizuo, indicating that there is a relatively stable and long-term continuous migration path of water and soluble salt inside the structure.

One possible explanation concerns the structural connection between the Ming Tower and the underlying Square City. Archaeological research at Ming Dynasty Xiaoling Tomb indicates that the tower walls extend into the supporting platform [13]. A comparable arrangement may exist at Ming Dynasty Kangling Tomb, but it has not been directly verified in the present investigation. If present, this continuity could facilitate downward moisture transport through the masonry. At Ming Dynasty Kangling Tomb, the vertical surface streaks extending across the brickwork and onto the Xumizuo are consistent with downward water movement along the façade, but do not by themselves demonstrate an equivalent pathway inside the structure.

Secondly, the material interface in the masonry composite structure further strengthens the water migration behavior. Square City & Ming Tower is composed of brick walls and Xumizuo stone components, forming a typical masonry composite masonry system. Due to the obvious differences in porosity, water absorption capacity, moisture conductivity and evaporation characteristics between brick and stone, water does not diffuse evenly inside the structure, but tends to flow along the material interface. Due to the strong pore continuity, this interface area often becomes the preferred migration path after rainwater infiltration. Part of the water will continue to move downward along the inside of the wall, while the other part will flow directly down along the façade of the square city, and finally collect at the junction area between the base of the wall and the Xumizuo.

This water migration method keeps the roots of Square City in a proposed complex two-way hygroscopic environment mechanism for a long time. On the one hand, the upper leakage water continues to be transported downward; On the other hand, the water in the Xumizuo and the ground environment will rise upwards through capillary action. Under the combined action of upper and lower two-way moisture, the bricks at the root of the wall are in a state of high humidity for a long time, and their internal pores repeatedly experience water absorption and evaporation cycles, resulting in the bricks are more prone to crisping, peeling and loose structure. A large number of brick breakage and whitening can be observed at the site, concentrated in the lower part of the wall, reflecting this continuous moisture enrichment process.

The reconstruction and repair history of Ming Dynasty Kangling Tomb provides an additional context for interpreting the present deterioration. White deposits are visible on damaged brick surfaces and on some repaired joints. Their spatial association raises the possibility that differences between original and repair materials affect local moisture transport and deposition. However, the present survey does not establish whether the repair mortars are a source of soluble salts or whether deposits have accumulated on them after transport from elsewhere. This distinction requires comparison of the composition and moisture-related properties of the original and repair materials.

Internal mortar filling associated with the traditional use of five-faced dressed bricks may also contribute to moisture and salt transport at Ming Dynasty Kangling Tomb. If water penetrates the masonry and reaches the mortar-filled spaces, it could dissolve soluble constituents, where present, and transport them through connected pores and joints. Prolonged water movement could also cause localized leaching or loss of mortar, potentially creating additional voids that alter subsequent moisture pathways. These processes provide a possible explanation for the surface deposits observed at Ming Dynasty Kangling Tomb, but neither internal mortar loss nor the contribution of the filling mortar to the salt deposits has been directly verified in this study. Examination and analysis of the internal mortar would be required to test this interpretation.

Under the action of gravity, the saline water eventually gradually flows towards the Xumizuo constellation region. Due to the complex geometric turning relationship of the Xumizuo itself, such as the Waist Section, upper cyma molding, recessed band and other parts of the collection and external picking, the water flow is easy to slow down and retain in these areas and form a local evaporation enhancement area. Therefore, these locations tend to be the areas where salt enrichment and crystallization are preferential. At the same time, when the salty water migrating from the inside of the wall flows through the surface of the Xumizuo, it may also react chemically with the substances contained in the marble itself, further forming new mineral deposits and stalactite-like secondary crystallization.

4 Conclusions

The investigation at Ming Dynasty Kangling Tomb documented a spatially differentiated pattern of visible deposits and deterioration on the Square City and its marble Xumizuo. The principal observations comprise a colour boundary near the level of the arched entrance, whitening

and material deterioration in the lower brickwork, vertical streaks extending across the brick–stone junction, and localized deposits on the waist, upper cyma molding, and recessed bands of the pedestal. These features define the areas of concern identified by the present survey.

The contribution of this case study lies in relating this observed distribution to the construction details and intervention history of Kangling. The brick-stone junction and the changes in the pedestal profile provide specific locations at which moisture transport, retention, and evaporation may contribute to deposition. The documented reconstruction and repairs also make the relationship between original masonry and repair materials an important question for further investigation. Their respective contributions to the present deterioration have not yet been established.

The proposed transport mechanisms remain preliminary. Downward infiltration, capillary moisture supply, and leaching from mortar are possible explanations rather than directly measured processes. In particular, structural continuity between the Soul Tower walls and the Square

City is inferred from comparative architectural evidence and has not been verified at Kangling. Mineralogical analysis and moisture monitoring are needed to distinguish deposit types, assess possible salt sources, and test the proposed pathways.

For Kangling, the immediate conservation priority is therefore targeted investigation of the lower brickwork, the brick-stone junction, and the deposit-bearing moldings of the xumizuo. Paired sampling of affected and less affected areas, examination of original and repair mortars, and monitoring of wetting and drying at these locations would provide a basis for selecting compatible interventions. The observations offer a basis for comparison with other imperial mausoleums, but their applicability elsewhere requires verification against local construction and exposure conditions.

Acknowledgements

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