

Integrated Architectural Documentation and Multi-Analytical Characterisation of Historic Lime Mortars in the Tomb of Ali Mardan Khan, Lahore, Pakistan

Muhammad Abdullah¹, Aleeha Saleem², Nosheen Blouch³, Nijah Akram⁴, Mohsin Iqbal Deo⁵ & Ahsan Khalil⁶

¹Department of Architectural Engineering Technology, Punjab Tianjin University of Technology, Lahore, Pakistan, Email: 23-ar-009@students.ptut.edu.pk.

²Department of Architectural Engineering Technology, Punjab Tianjin University of Technology, Lahore, Pakistan, Email: 23-ar-014@students.ptut.edu.pk.

³Department of Building and Architectural Engineering, Faculty of Engineering & Technology, Bahauddin Zakariya University, Multan, Pakistan, Email: nosheenbalouch@bzu.edu.pk.

⁴Department of Architectural Engineering Technology, Punjab Tianjin University of Technology, Lahore, Pakistan, Email: akram.nijah@ptut.edu.pk

⁵Assistant Professor, NFC-IET Multan, Pakistan, Email: Mohsin.deo@gmail.com.

⁶Department of Architectural Engineering Technology, Punjab Tianjin University of Technology, Lahore, Pakistan, Email: ahsan.khalil@ptut.edu.pk.

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Corresponding Author:

Nijah Akram

Email:

akram.nijah@ptut.edu.pk

ABSTRACT

Mughal architectural heritage conservation needs a holistic understanding of its spatial organisation and the performance of its construction systems. This research investigates the Tomb of Ali Mardan Khan in Lahore, a 17th-century (1656-1657) Mughal funerary building, in terms of architectural recording and material analysis. The monument is a mature example of Mughal architecture with an octagonal plan, a double-dome structure, a high drum, chattris and a sophisticated decoration. Despite its historical and architectural importance, the structure is in a state of severe deterioration, as a result of environmental factors, plant growth and unsympathetic restorations. We employed a multi-disciplinary approach, which combined architectural documentation with laboratory analysis for material characterisation, specifically X-ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX) and water absorption. The architectural survey captured the spatial arrangement, structural hierarchy, and the decorative elements of the tomb, including the entrance, dome system, burial chamber and other decorative elements. XRF analysis shows high lime content (calcium and silica), consistent with non-hydraulic lime mortars with siliceous aggregates. FTIR analysis confirms calcite as the dominant binding phase, and SEM-EDX shows a highly porous structure with a weak bond between binder and aggregate, and small hydraulic phases. High porosity and water absorption are also confirmed by water absorption tests. This combined approach shows a high level of incompatibility between original lime-based materials and subsequent cementitious repairs, accelerating the deterioration of materials. The research emphasises the need for compatibility-based conservation and the use of architectural documentation and material science for evidence-based restoration of Mughal monuments.



1. Introduction

Traditional masonry monuments are a vital part of cultural heritage and have provided a testament to architectural knowledge, skills, and regional building materials for generations. Domes and vaults are some of the most iconic structural elements in Islamic architecture, and have developed through time and place [1-3]. Mughal-style architecture in particular combines elements of Persian, Central Asian, and indigenous architectural styles to produce impressive monuments and religious buildings, which are still valuable assets today [4-6]. They were largely constructed with lime-based mortars, which have historically offered sufficient strength, flexibility, and vapour permeability for long-term durability.

With time, historic masonry is subject to natural weathering, water penetration, salt crystallisation, and biological attacks, leading to decay of mortar joints and plaster. Cement-based mortars have been extensively used for repair purposes in many conservation projects due to their availability and rapid early strength development. However, it has been shown that cement-based materials are incompatible with historic lime-based mortars in terms of stiffness, permeability and composition, which may result in accelerated deterioration and loss of historic materials [7, 8]. As a result, compatible lime mortars for repair are a key focus of modern conservation.

Characterisation of historic mortars has become an important topic of conservation studies. Methods like X-ray fluorescence (XRF), X-ray diffraction (XRD) and scanning electron microscopy (SEM) are commonly employed for characterisation of chemical, mineralogical and microstructural properties of historic materials [9-11]. Existing research shows that knowledge of the original composition is crucial for developing repair mortars with similar physical and mechanical properties to historic masonry [12, 13]. However, many historic buildings in South Asia lack in-depth studies and repair and restoration are often carried out without proper material analysis.

Lahore is home to several Mughal monuments that are important architectural and cultural heritage [14, 15]. Recent research has stressed the need for documentation and conservation of historic buildings in this region due to the deterioration and conservation issues [16-19]. One such structure is the Ali Mardan Khan Tomb, which has undergone continuous deterioration and several repairs using unsuitable materials. But there has been no systematic study to understand the composition and properties of its historic mortar.

Hence, the objective of this study is to assess the historic mortar of the monument and to formulate a similar lime-based repair mortar for conservation. The specific objectives of the study are as follows:

1. To determine the physical, chemical, and mineralogical properties of original mortar samples;
2. To analyse the microstructural characteristics of the historic material using advanced analytical techniques; and
3. To design a compatible repair mortar based on the characterisation results to support sustainable conservation of historic masonry.

Table 1. Reviewed Literature

Ref	Authors & Year	Objectives	Methods	Findings	Research Gap
[1]	Younan et al., 2024	Evolution and environmental performance of domes	Comparative architectural & environmental analysis	Domes provide thermal efficiency and structural performance in historic climates	Limited material-level analysis of mortars
[2]	Ashkan & Ahmad, 2010	Double-shell domes in Islamic architecture	Historical & morphological analysis	Dome geometry evolved with advanced construction techniques	Lack of material characterisation of mortar systems
[3]	Cowan, 1977	History of masonry domes	Historical structural analysis	Masonry domes rely heavily on lime-based materials	No conservation-focused material studies
[20]	Moustafa et al., 2018	Thermal behaviour of vaults and domes	Simulation-based study	Domes improve thermal comfort in hot climates	Material deterioration was not addressed
[12]	Marushchak & Pozniak, 2022	Thermal performance of wall materials	Thermal parameter analysis	Traditional materials show better thermal regulation	Need for conservation-compatible materials
[13]	Petkova-Slipets et al., 2020	Traditional vs modern wall materials	Comparative thermal analysis	Traditional materials perform better in breathability	Compatibility issues of modern repairs
[8]	Liritzis et al., 2015	Mortar analysis for conservation	Chemical & mineralogical analysis	Mortar characterization essential for restoration	Need for case-specific repair mortar design
[9]	Tao et al., 1990	XRF for material analysis	XRF methodology	XRF is effective for chemical characterisation of building materials	Application to heritage mortars required
[10]	Ural, 2021	SEM microstructure analysis	SEM review study	SEM essential for studying porosity and bonding	Limited application in South Asian heritage
[11]	Moretti et al., 2020	SEM-EDS statistical analysis	SEM-EDS & statistical modeling	Microstructure strongly affects mechanical performance	Need for integration with conservation studies
[7]	Costigan & Pavía, 2010	Lime mortar workability and performance	Mechanical and material testing	Water content strongly affects lime mortar behaviour	Need for site-specific repair mortar formulations
[16]	Kashif et al., 2025	Mughal tomb architecture in Lahore	Architectural analysis	Mughal tombs are under-researched heritage assets	Lack of material science studies
[17]	Khan & Bilal, 2025	Historic tomb documentation	Architectural documentation	Urgent conservation needs in Lahore monuments	No mortar characterisation studies
[21]	ul Haq et al.,	Conservation	Documentation &	Incompatible repairs	Need for scientific

	2025	challenges in heritage buildings	conservation study	are major threats	conservation materials
[19]	ul Haq et al., 2025	Historic building conservation	Architectural & conservation analysis	Conservation requires material compatibility	No experimental mortar design

The reviewed literature (Table 1) demonstrates extensive research on the architectural evolution and structural performance of domes, as well as growing interest in material characterisation for conservation purposes. However, limited studies integrate detailed mortar characterisation with the development of compatible repair mortars, particularly in the context of Mughal heritage in South Asia. This gap highlights the need for site-specific scientific investigations that combine material analysis and conservation-oriented repair design.

2. Case Study: Architectural Documentation of the Tomb of Ali Mardan Khan

2.1. Historical Background and Significance

The Tomb of Ali Mardan Khan, in Mughalpura, Lahore, is a 17th-century Mughal funerary structure built in 1656-7. Although the monument is an important architectural and historical landmark, it remains a neglected subject in academic studies and restoration. The monument is presently located on the compound of the Pakistan Railways Workshop and is approached through a closed gate, which has played a pivotal role in its isolation and invisibility [4].

Ali Mardan Khan was a Mughal governor, engineer and military officer who served the Safavid court before defection to the Mughal court in 1638. After serving the Mughal emperor, Shah Jahan, he was given important administrative appointments such as governorships of Kashmir, Punjab and Kabul [15]. He is known for his work in canal irrigation, fortification, and urban planning, and is a prime example of the architect-administrator.

The tomb is a testament to his status and represents the later phase of Mughal funerary architecture, with a sophisticated geometry, decoration, and massiveness [4].

2.2. Site Context and Spatial Configuration

The tomb is a part of a historical garden that was originally part of a Mughal chāhār bagh (four-part garden) complex, of which almost nothing remains today because of urbanisation and railway construction [22]. The northern gate is the only remaining part of the garden, and it is now within the "no-man's-land" of the railway compound, permanently gated with iron grillwork since the British colonial era [23] (Figure 1).

The tomb is located on an octagonal plinth and is accessible via staircases on the north and south. On cardinal sides at the plinth level, the spatial arrangement of water tanks is present, albeit now dried out and decayed. There are no traces of fountains and garden paths, pointing to a highly deteriorated landscape (Figure 2).

2.3. Architectural Typology and Structural Form

The tomb is a pure octagon, a common theme in mature Mughal funerary architecture, and is conceptually related to earlier Islamic and Central Asian monuments like the Dome of the Rock (691 CE) and Qubbat al-Sulaibiya at Samarra [5].

The octagon's facades have four-centred archways, which are further divided into portals and ventilated arches. The dome is seamlessly connected to the octagonal base through pendentives, showcasing Mughal structural ingenuity. It is topped by a double-dome system, set on a large drum, estimated to be 200 ft in diameter and 60 ft high. The disproportionate proportions between

the dome and the base reflect experimental architectural proportions of Shah Jahan's monumental tombs.

The octagon is adorned at each corner with chattris (kiosks) of which only three remain. These, built through corbelled brickwork, are both functional and decorative, and reduce bulkiness and add to skyline articulation (Figure 3).

2.4 Gateway Architecture and Decorative System

A two-storey rectangular building, divided by small side arches and topped by a large central arch, is the northern gateway. The façade has been embellished with muqarnas stucco, three-centred arches and vaulting and conforms to the Mughal typology of gateways in the city of Lahore in the middle of the 17th century [24]. Comparative studies do show an architectural correlation with the gateways of the tomb erected by Asif Khan (1645) and the Chauburji Monument (1646), particularly as far as design on the façade and the decoration using stucco is concerned.

Faience mosaic, fresco and stucco decoration were widely used, but are mostly eroded at present and can be seen in decoration analysis. It is also adorned with cloud and vase form attachments and floral cartouches, which, combined with Indo-Persian decorative elements (Figure 4).

2.5 Dome, Drum, and Upper Architectural Elements

The dome is constructed from a double-shell building together with a big drum. The drum has a blind arcade and stylised lotus designs, representing the celestial ascent and structural continuity. On the lower part of the dome, there remain some remains of mosaics and floral vines; originally, the lower surface of the dome was totally covered with marble and stucco decoration. Another important clue to the functional character of the ornamental system (which is not yet explored) is the presence of the pigeonhole on the base of the dome.

The design of the kiosks found at the corners of the octagon, which is in keeping with Mughal philosophy of balanced monumentality, adds to the balance and harmony between the vertical and horizontal features.

2.6 Interior Spatial Organisation and Burial Chamber

Inside is an octagonal room with niches with arches. The original cenotaph was located over a burial chamber, accessible by a staircase close to the southern door, in the central platform (Figure 5). There are three graves in this chamber, one with a Persian inscription named Ali Mardan Khan, while the other two are believed to be of his family members [25]. Plaster, muqarnas and floral ornamentation are seen on the ceiling of the chamber, although much of the ceiling surface is worn. The interior decorations that remain in the structure feature acanthus leaves, vine scrolls and European florals, similar to those found in the tomb of Asif Khan and later Mughal structures built in Lahore [26].

2.7 Materiality and Decorative Synthesis

The tomb demonstrates a complete repertoire of seventeenth-century Mughal decorative techniques, including:

- Faience mosaic (gateway façade)
- Fresco painting (arches and muqarnas segments)
- Stucco relief work (interior dome and vaults)
- Inlay decoration (dome surface remnants)

The ornamentation reflects a tripartite synthesis of artistic influences:

Indigenous Indian floral traditions, Safavid Persian islimi-khata'i patterns, and emerging European naturalistic motifs [6, 26]. This fusion is particularly evident in floral compositions, vase motifs, acanthus leaves, and cloud bands, indicating the maturity of Mughal decorative vocabulary during Shah Jahan's reign.

2.8 Current Condition and Conservation Status

Heated by the environment, neglected by its visitors, and subject to a colonial/post-colonial adaptive re-use process that has been ongoing for some time, the monument is now very close to the point of advanced decay. Signs of structural decay include the loss of plaster, the multi-layered nature of the erosion of decorative materials and the breakdown of peripheral architectural elements. The growth of vegetation, moisture infiltration and fire exposure have also exacerbated material degradation, especially in the dome and interior work of plaster. No conservation programme has been in place, and this has led to the progressive loss of architectural integrity.

This study includes the following documentation outputs:



Figure 1. Site Location and Contextual Map

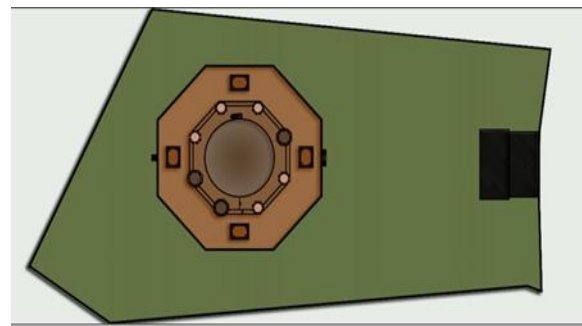


Figure 2. Existing site plan and plinth-level layout

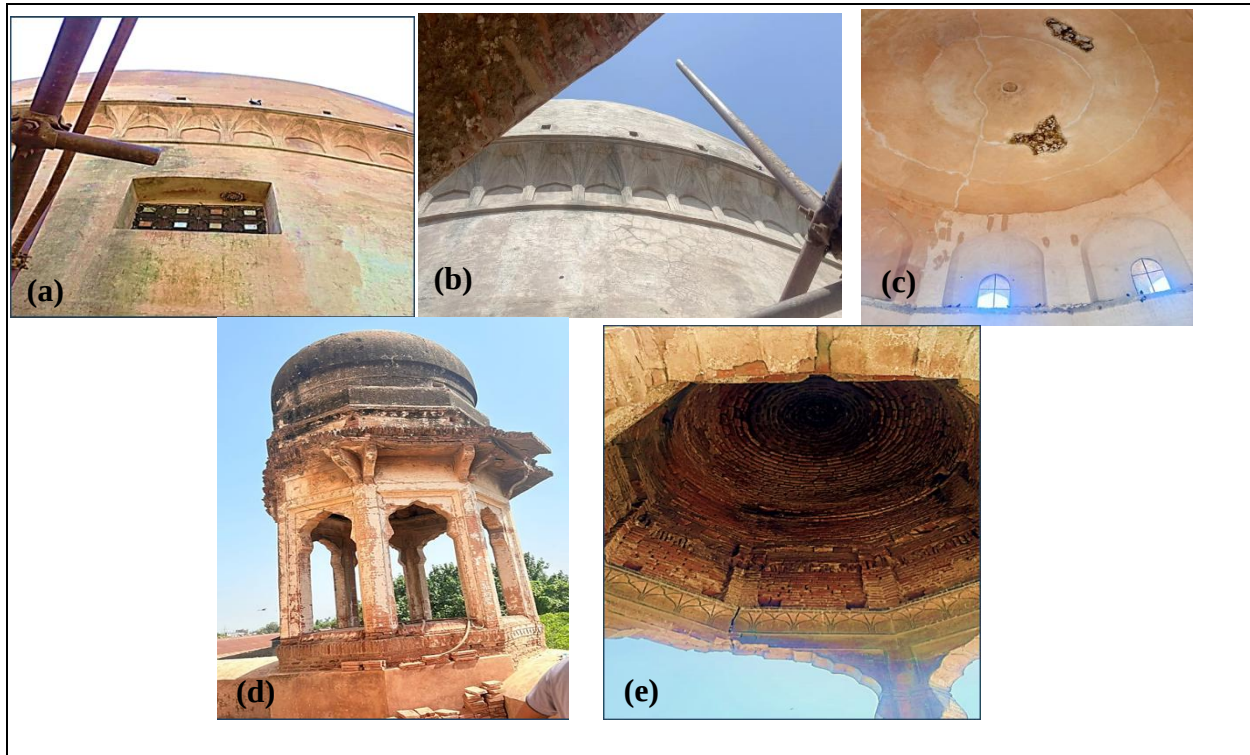
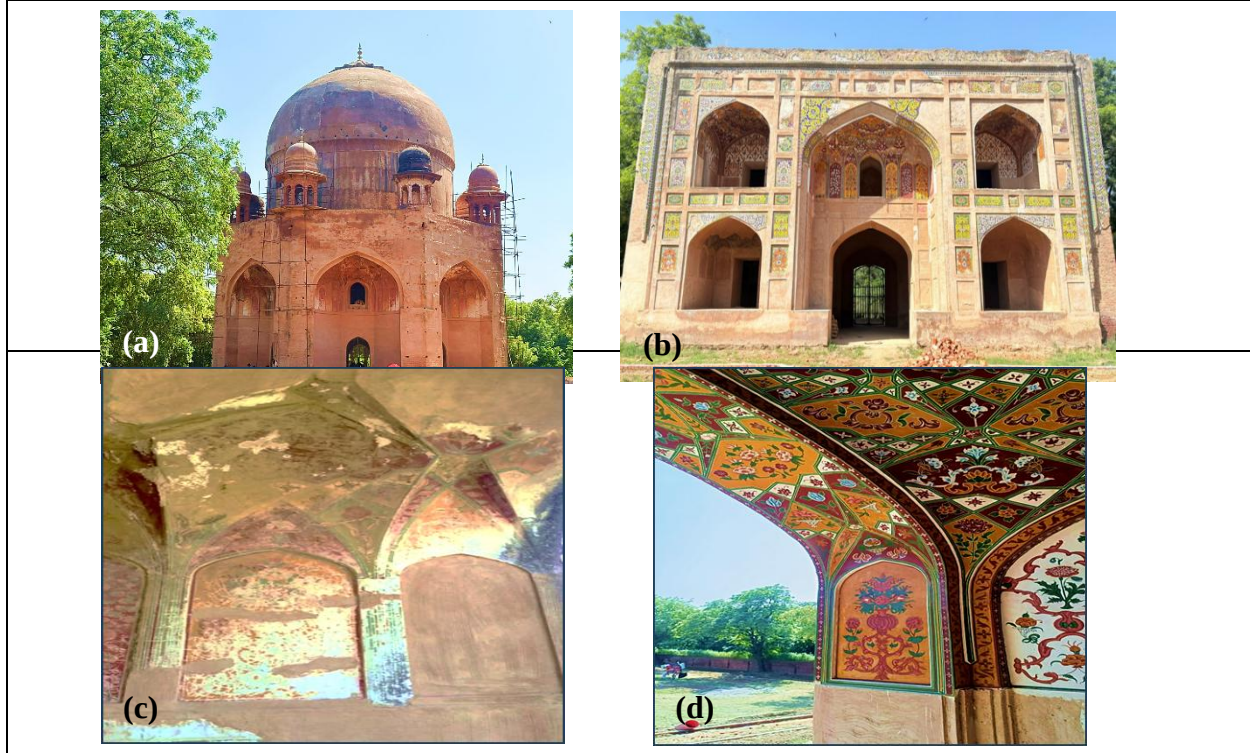


Figure 3. Architectural detailing of the dome and drum: (a) Decorative elements crowning the drum, (b) Fragmented ornamentation along the dome neck, (c) Surviving incised stucco on the inner dome surface, (d) Corner kiosks positioned above the octagonal edges, (e) Interior view of the subsidiary kiosk cupola.



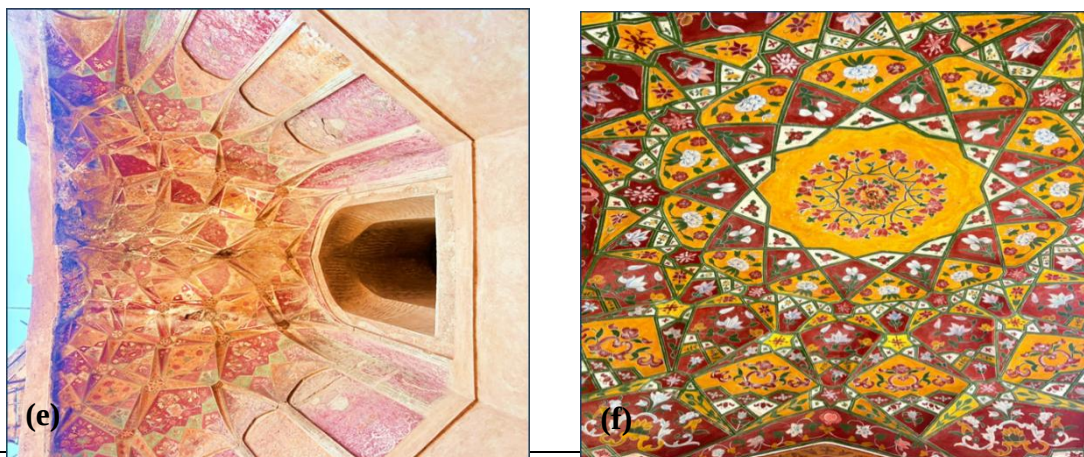
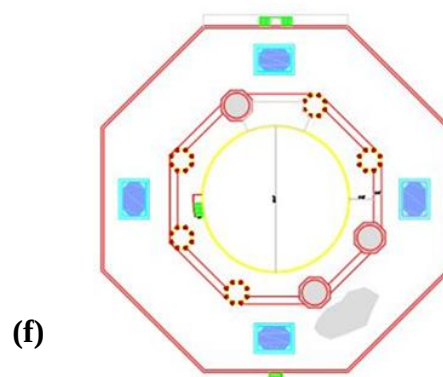
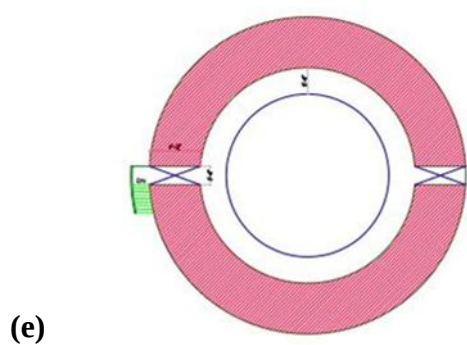
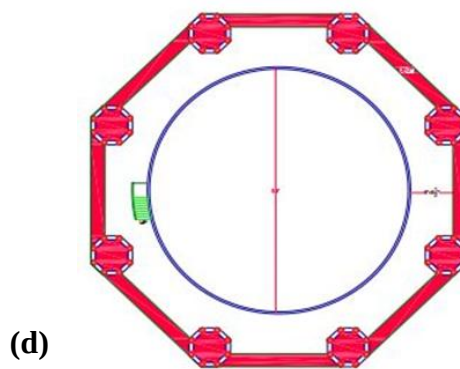
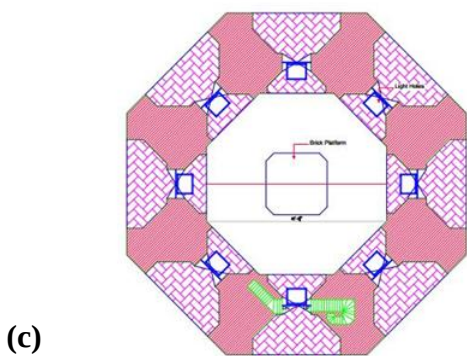
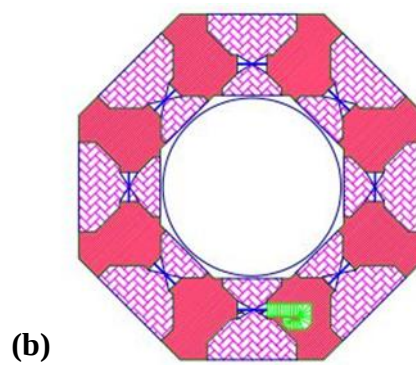
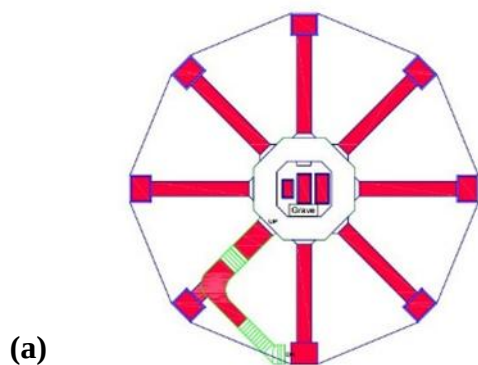


Figure 4. Gateway façade and decorative analysis: (a) Front façade, (b) Rear façade of the gateway, (c–d) Faience mosaic panels from the lower side arches of the south façade of the gateway, (e) Remains of fresco painting within the arched recesses of the tomb, (f) Muqarnas fragment from the octagonal tomb recess featuring a sunflower motif as the central element.



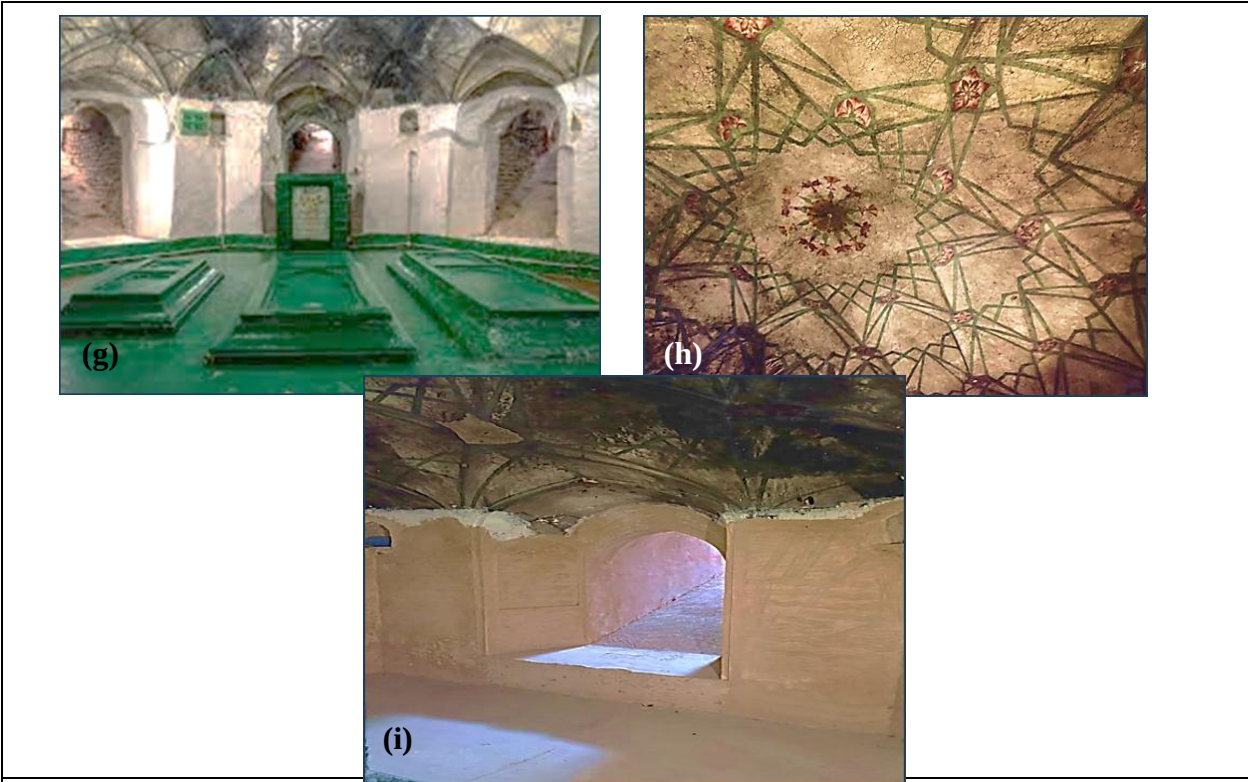


Figure 5. Interior plan and burial chamber layout: (a) Basement layout, (b) Mezzanine floor plan, (c) Ground floor plan, (d) Roof plan, (e) Double-dome configuration, (f) Overall top view layout, (g) Underground burial chamber and grave, (h) Ceiling of the subterranean chamber, (i) Interior view of the burial hall arches.

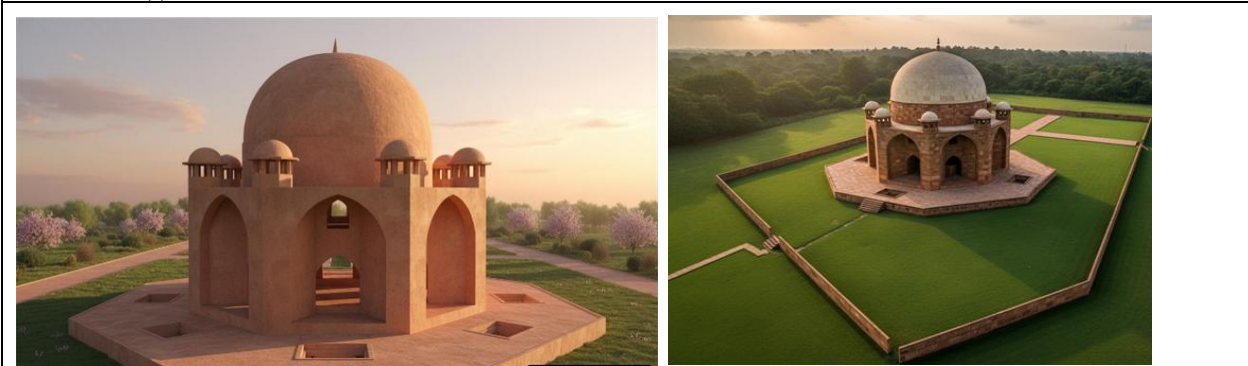


Figure 6. Digital Model of the Tomb of Ali Mardan

Table 1. Summary of Architectural and Material Characteristics of the Tomb of Ali Mardan

Category	Feature	Description	Significance
Historical Context	Construction Period	Built 1656–1657 during the reign of Shah Jahan	Mature Mughal funerary architecture
	Patron	Governor, engineer and architect Ali Mardan Khan	Strong Safavid–Mughal cultural linkage
	Original Setting	Part of the garden corridor linking to Shalimar Gardens (charbagh layout)	Indicates elite funerary landscape planning

Site Context	Present Location	Inside Pakistan Railway Workshop, Mughalpura, Lahore	Restricted access and neglect
	Access Condition	Narrow grilled passage; limited public visibility	Contributes to poor conservation
Architectural Typology	Plan Form	Octagonal mausoleum on a raised platform	Characteristic Mughal tomb typology
	Structural System	Double-dome construction	Climatic and symbolic architectural solution
	Influences	Iranian, Indian and European stylistic synthesis	Represents hybrid Mughal decorative vocabulary
Platform & Landscape	Podium	Raised octagonal platform with staircases north & south	Monumental elevation and symmetry
	Water Features	Four cardinal water tanks on a plinth	Remnants of Mughal garden symbolism
Gateway (Chintgarh)	Gateway Form	Double-storey gateway with three-centred arches	Typical Mughal entrance composition
	Decorative Elements	Faience mosaic, frescoes, stucco muqarnas	Rich ornamental gateway surviving today
Exterior Architecture	Drum & Dome	Large drum and massive double dome; lotus-petal band	Monumental skyline presence
	Corner Elements	Octagonal kiosks (chattris) at corners	Indigenous Mughal design feature
	Materials	Kiln-burnt brick masonry with plaster finish	Standard Mughal construction practice
Interior Layout	Main Hall	Octagonal hall with arched recesses and windows	Efficient transition to the dome via pendentives
	Burial Chamber	Underground chamber with three graves	Typical Mughal burial arrangement
Decorative Program	Surface Ornament	Fresco painting, stucco, faience mosaic, marble inlay (fragmentary)	Multi-material decorative system
	Motifs	Floral, acanthus leaves, cloud bands, vases, lotus	Fusion of Safavid, Mughal and European motifs
Condition Assessment	Structural State	Loss of plaster, frescoes and marble inlay	Advanced deterioration
	Conservation Status	Severe neglect and	Urgent conservation

		environmental damage	required
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Recent research highlights the growing integration of sustainability, material science, and digital technologies in construction and heritage conservation [27]. Artificial intelligence and data-driven approaches are increasingly used to improve project planning and lifecycle performance of built assets [28, 29]. The development of eco-friendly construction materials, including fly ash, hemp, and agro-industrial waste, demonstrates improved performance and reduced environmental impact, supporting the relevance of material optimisation for conservation work [30-33]. Studies on LC3 composites and wastewater-integrated concrete further emphasise the importance of binder composition, pozzolanic reactions, and durability assessment [30, 34-37]. Sustainability research also stresses energy-efficient design [38-43], environmental modelling, and interdisciplinary approaches that combine digital documentation with material analysis for better conservation strategies [18, 44-48].

The Tomb of Ali Mardan Khan is an important piece of "mature Mughal funerary architecture," and exhibits a highly developed architectural vocabulary in its decoration and structural engineering (Figure 6). The monument is in a poor state of repair and has been seriously disregarded both architecturally and historically. Not only does the architectural documentation provided in this study set a baseline for conservation planning, but it also creates a body of knowledge regarding Mughal architectural evolution in Lahore, which would benefit the conservation planning process for the city (Table 1).

3. Materials and Methods

The study involves both experimental and analytical methods to study the physicochemical and microstructural characteristics of historic lime mortar samples and to formulate a repair mortar for the repair of Ali Mardan Khan Tomb, Lahore, Pakistan. The methodology adopted combines the on-site sampling, laboratory tests for material characterisation, and mix design for conservation procedures (Figure 8). This workflow follows up the conventional approach practised in historic material analysis and conservation science that involves the use of multiple analytical tools to shed light on the physical, chemical, and mechanical aspects of materials in heritage structures [8-11].

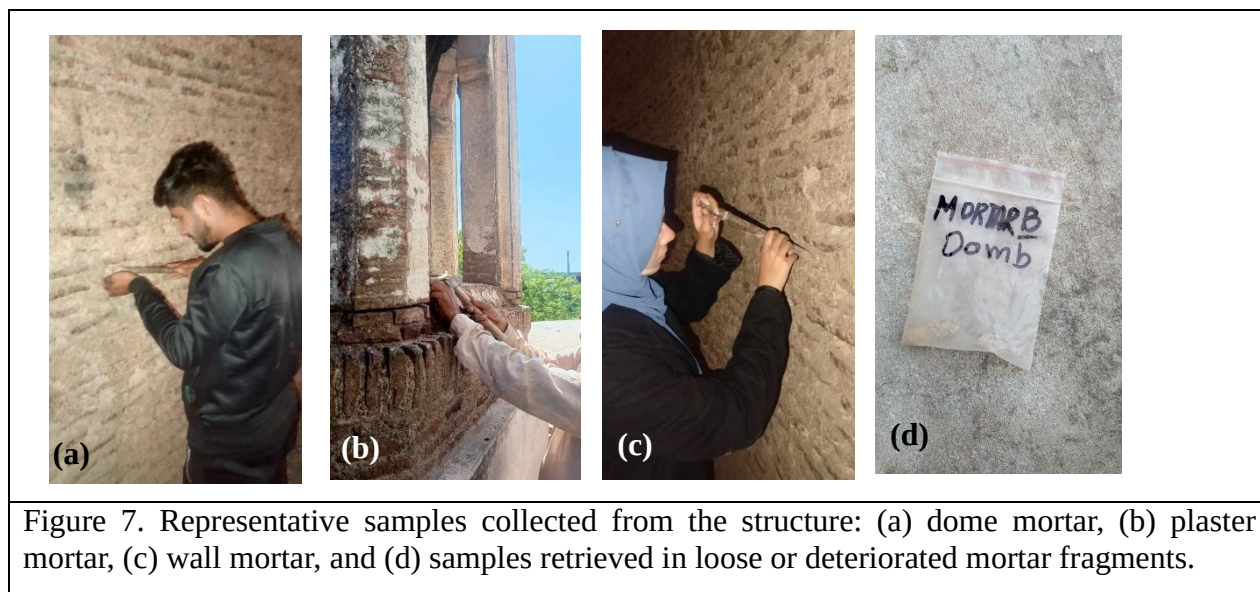
3.1 Sampling Strategy

Samples of the Ali Mardan Khan Tomb mortars were obtained using a non-destructive and minimally invasive sampling approach to maintain the integrity of historic buildings. The samples were taken from areas with visual deterioration mapping and easy access to the original materials. The samples were taken in the form of loose or crumbling mortar from locations where no recent repairs had been carried out to prevent any external contaminants from cementitious material.

The following representative samples were collected: (i) dome mortar, (ii) wall mortars, and (iii) plaster mortars (Figure 7). The samples were tagged and recorded based on their origin for detailed investigation. Sampling is carried out in accordance with the usual practice of heritage material studies, where the representativeness and stratigraphic context are crucial for meaningful interpretation of analytical data [8].

Mortar samples were initially cleaned by hand to remove surface dirt, vegetation, and other contaminants. Subsequently, they were dried in an oven at 60 °C for 24 hours to a constant weight to remove any moisture that might interfere with the analyses [49]. The fragments were then ground into a fine powder using a mortar and pestle and sieved for homogenisation to prepare samples for chemical and mineralogical characterisation [50].

For microstructural studies, some fragments were mounted and sputter-coated with a thin gold layer to enhance image quality for electron microscopy. This sample preparation protocol was consistent with that used for archaeological and conservation materials for reproducibility and analytical accuracy [10, 11].



X-Ray Fluorescence (XRF) Analysis

X-ray fluorescence (XRF) spectroscopy was used to determine the elemental and chemical composition of the historic mortar samples. The powdered specimens were prepared as pressed pellets and analysed using an energy-dispersive XRF spectrometer. The technique provides quantitative data on major and minor oxides, including CaO, SiO₂, Al₂O₃, Fe₂O₃, and MgO.

XRF analysis is widely used in conservation science for identifying binder types and evaluating material compatibility between historic and repair mortars [51] due to its non-destructive nature and high analytical precision [9]. The results obtained were used to classify the mortar as lime-based and to assess the degree of hydraulicity, which is essential for designing compatible repair materials.

Fourier Transform Infrared Spectroscopy (FTIR)

Functional groups and bonding characteristics in the mortars were determined using Fourier Transform Infrared Spectroscopy (FTIR). Spectra were recorded in the spectral range 4000-400 cm⁻¹. FTIR analysis can reveal the presence of carbonate, silicate and hydroxyl groups, which are indicative of carbonation of lime and the presence of hydraulic phases.

FTIR is especially adept at identifying differences between calcite binders and alteration minerals in historic mortars as a result of weathering events. This method can be used in conjunction with XRD and XRF to better understand phase transformations in lime-based products [8].

Scanning Electron Microscopy with Energy Dispersive X-ray (SEM-EDX) Analysis

The microstructural morphology and the distribution of elements in the mortar samples were studied using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray spectroscopy (EDX) techniques. SEM offers the very high resolution imaging of pore structures, interfaces between the binder and aggregates, and microcracks, and the EDX facility allows for localised elemental analysis [52].

This holistic technique is widely acknowledged as an effective instrument in conservation material research for elucidating deterioration mechanisms and microstructural development of lime mortars [10, 11]. The microstructural observations were used to evaluate porosity, cohesion, and degradation patterns, which are critical parameters for assessing material performance in historic masonry.

Water Absorption Test

Moisture transport and porosity investigation aimed to evaluate the moisture transport behaviour and porosity of the historic mortar samples. The test was conducted as a standard testing procedure for porous building material. Samples were first dried in the oven to a constant weight and then soaked in water for 24 hours. The weighed samples were taken out of the water after saturation and reweighed to calculate water uptake.

Water absorption percentage was calculated using the following expression:

$$WA (\%) = \frac{W_s - W_d}{W_d} * 100$$

Where W_s is the saturated weight, and W_d is the dry weight of the sample [53, 54].

Water absorption is an essential parameter in lime mortar research, as it directly influences pore structure, vapour permeability, and durability performance. Elevated water absorption values are typically linked to conventional lime mortars, which are crucial for compatibility with historic masonry systems [7, 12, 13].

Development of Compatible Repair Mortar

The results from XRF, FTIR, SEM-EDX and water absorption analysis were used to design an appropriate repair mortar, with Natural Hydraulic Lime (NHL) and local aggregates. The mix design aimed to meet the physical and chemical requirements of the original mortar, with increased durability and workability.

The formulation process considered:

- (i) Chemical compatibility derived from XRF results [9].
- (ii) Mineralogical similarity indicated by FTIR analysis.
- (iii) Microstructural behaviour observed through SEM-EDX [10, 11].
- (iv) Porosity and moisture transport properties obtained from water absorption tests [7].

This multifaceted technique ensures that the repair mortar retains compatibility regarding strength, permeability, and long-term performance, which are fundamental characteristics in heritage conservation management [8].

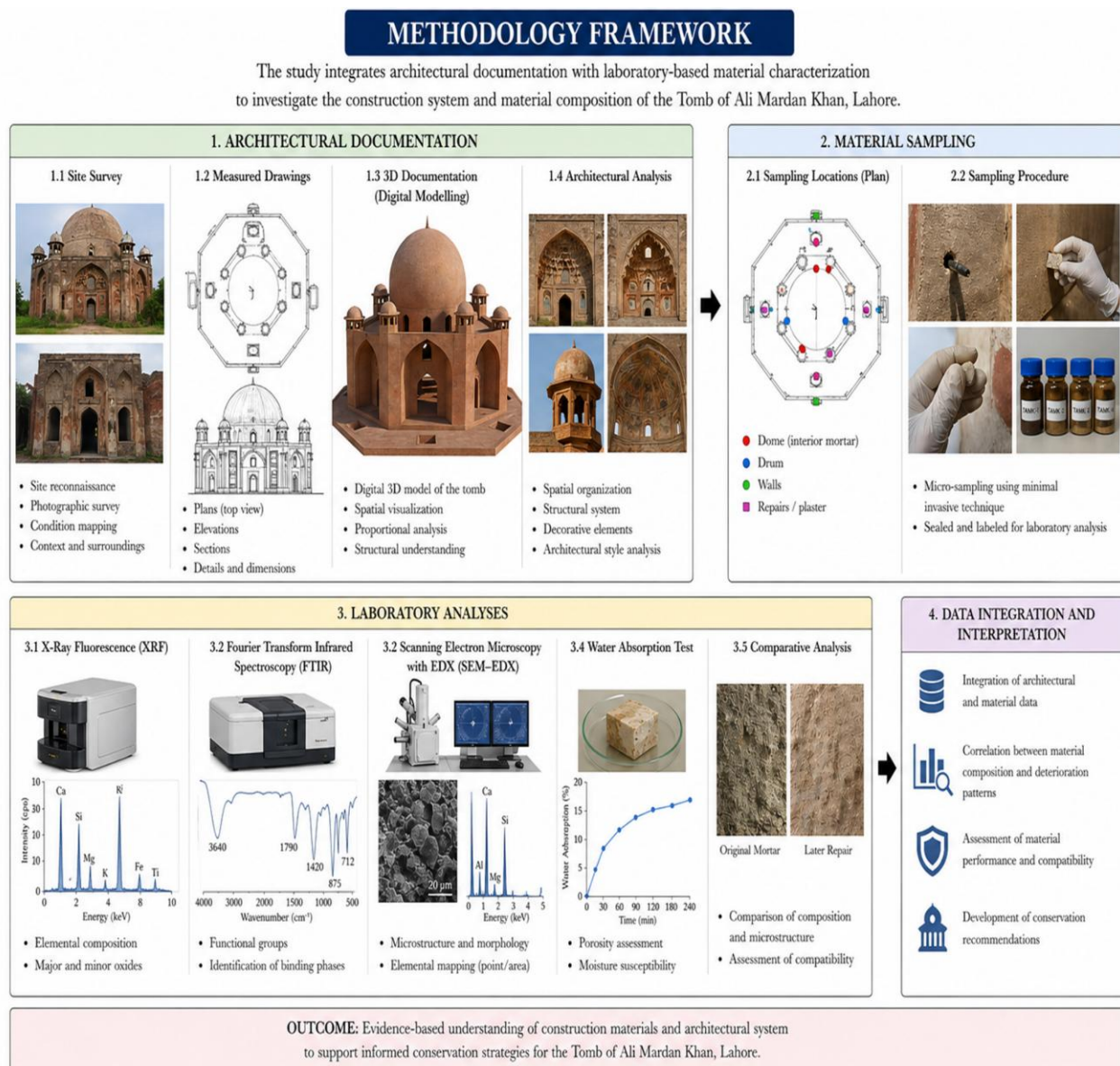


Figure 8. Methodology Framework

4. Results and Discussion

4.1. Analytical Workflow

4.1.1. Chemical Composition (XRF)

The historic lime mortar sample's X-ray fluorescence (XRF) analysis reveals that it is primarily composed of non-metallic silicate and carbonate phases without any precious or metallic phases, suggesting that it is a geological and building material rather than a metallic or industrially produced product. The major oxides include silicon (Si = 42.39%), calcium (Ca = 21.96%), and potassium (K = 16.36%), followed by iron (Fe = 6.98%), magnesium (Mg = 4.58%), aluminum (Al = 2.31%), sulfur (S = 0.87%), cobalt (Co = 1.22%), titanium (Ti = 0.32%), and minor light elements (3.00%) (Table 3, Figure 9).

Table 3. Percentage composition of materials in lime mortar

Sr.	Metal	Percentage %
1	Silicon	42.39
2	Calcium	21.96
3	Potassium	16.36
4	Magnesium	4.58
5	Iron	6.98
6	Cobalt	1.22
7	Aluminum	2.31
8	Titanium	0.32
9	Sulphur	0.87
10	light element	3.00

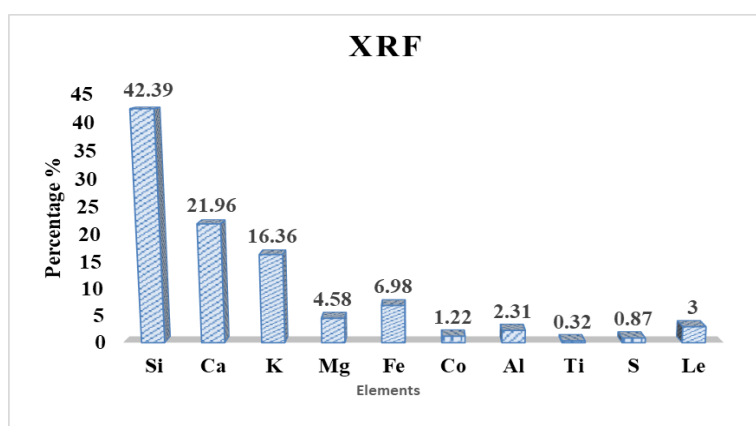


Figure 9. XRF analysis showing the percentage composition of materials

Siliceous sand and lime mortars, similar to traditional masonry mortars of the Mughal period, are indicated by the high proportions of SiO_2 and CaO . This high value of potassium may indicate that an aggregate contains high levels of feldspar or a high clay content, perhaps indicating that untreated sand has been used. Alluvial sands are indicated by the iron and magnesium content as well. In short, the mineralogical investigations confirm the presence of lime mortar, made from a non-hydraulic lime, with siliceous aggregates, typical of the use made in historic structures in South Asia [7-9].

4.1.2. Mineralogical Phases (FTIR)

FTIR spectra of the mortar sample (Figure 10) indicate the presence of multiple functional groups associated with lime carbonation and minor organic or silicate impurities.

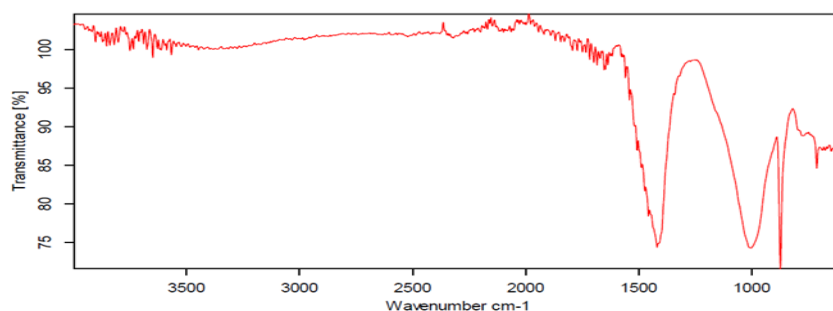


Figure 10. FTIR spectra of the mortar sample

The absorption peak around 3447 cm^{-1} is a broad peak likely attributable to O-H stretching vibrations, suggesting the presence of hydroxyl groups in the structure. The variations of CO_2 -related weak vibrations are indicated by peaks in the interval $2520\text{--}2319\text{ cm}^{-1}$. The strong peak in 1733 cm^{-1} indicates carbonyl (C=O) functional groups that can be related to carbonate formation or small amounts of organic contaminants. Infrared absorptions between 1653 and 1600 cm^{-1} are characteristic of C=C stretching or amide type modes, and absorptions from 1558 to 1507 cm^{-1} are associated with aromatic or N-H bending modes.

The strong band at 1418 cm^{-1} is seen to belong to carbonate (CO_3^{2-}) vibrations, which further establishes the formation of calcite. The peaks at 1002 cm^{-1} could be attributed to C-O stretching of alcohols and ethers; peaks in the fingerprint region (900 to 600 cm^{-1}) were characteristic of structures of both silicate and carbonate deformations. FTIR results overall agree that the mortar is mainly composed of a calcite-based lime mortar accompanied by a small contribution from silicate and organic components, consistent with the XRF and SEM results [8].

4.1.3. Microstructural Characteristics (SEM-EDX Analysis)

The historic mortar's microstructure is heterogeneous and very porous, with angular particles, broad micro spaces, and irregular binder distribution, according to SEM investigation (Figure 11-12). These characteristics relate to the masonry matrix's long-term weathering and moisture interaction.

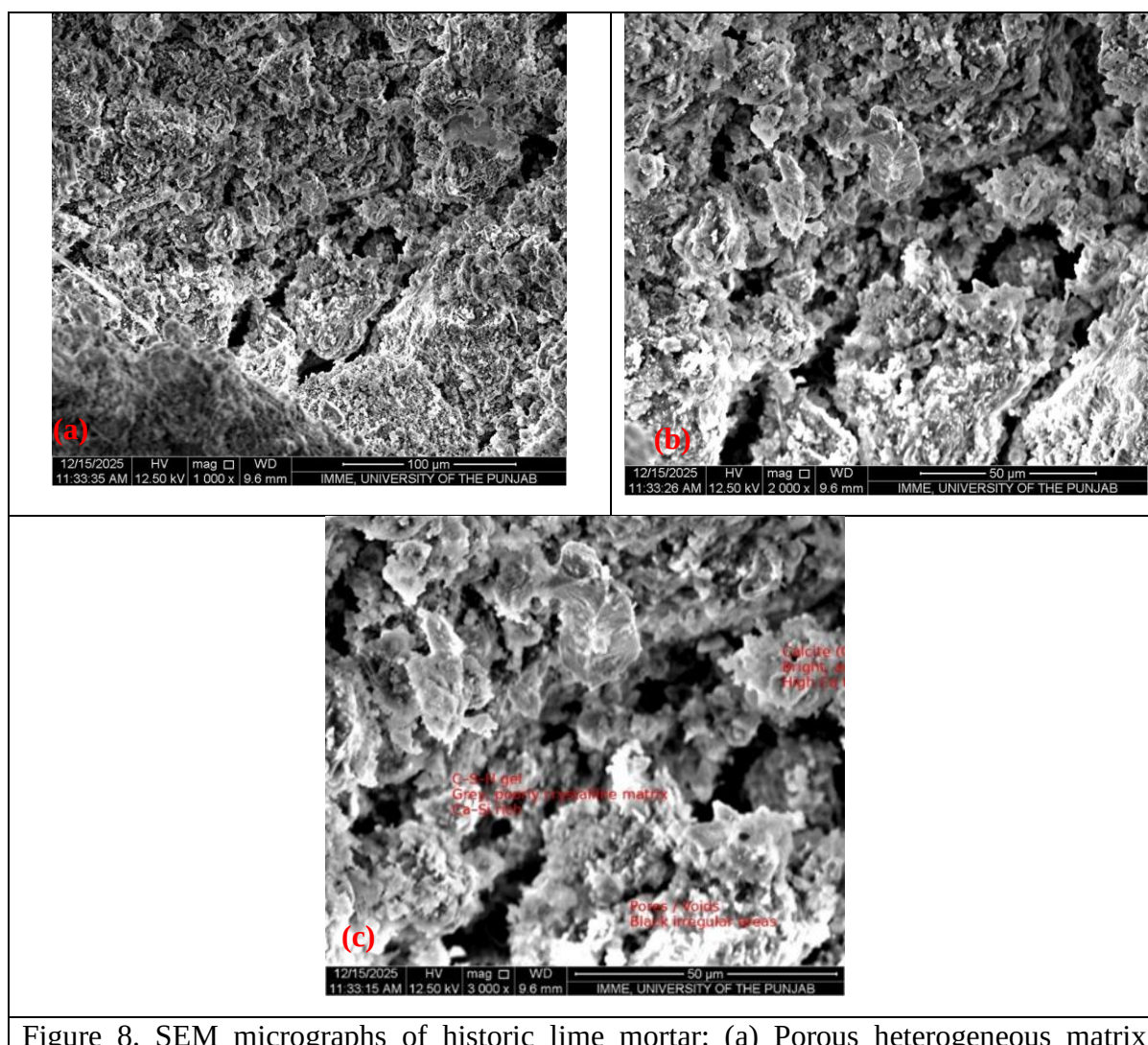


Figure 8. SEM micrographs of historic lime mortar: (a) Porous heterogeneous matrix

(1000×), (b) Binder–aggregate interface with pore network (2000×), (c) Calcite crystals, C-S-H gel, and voids indicating carbonation and weathering (3000×)

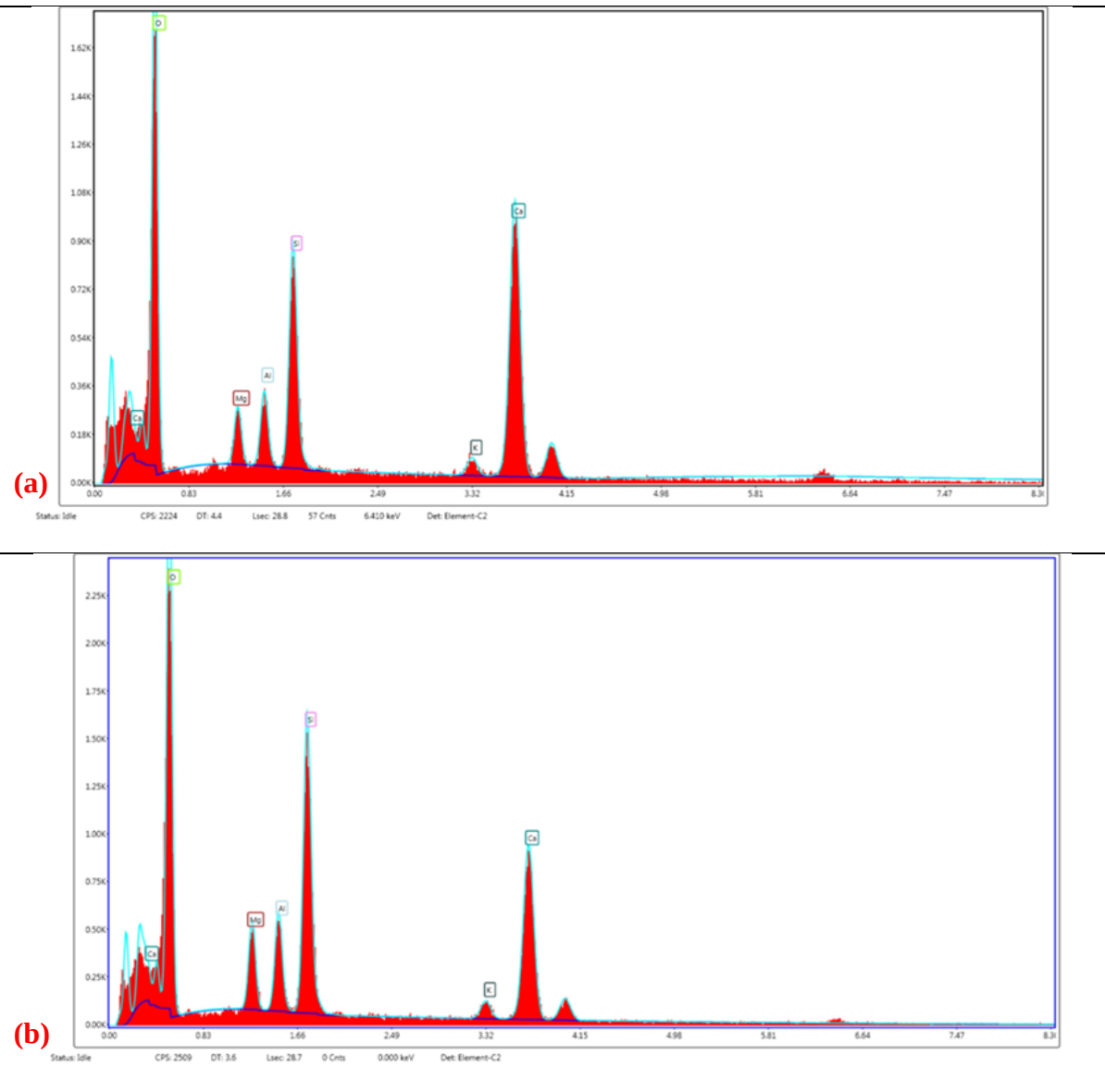


Figure 9. SEM-EDX spectra of mortar samples: Both spectra show dominant O, Si and Ca peaks with minor Al, Mg and K, confirming a calcium-silicate-rich mortar composition.

The lime binder phase was identified as Calcite (CaCO_3) as bright, angular calcite crystals. EDX results suggest that the structure is primarily composed of calcium carbonate, justifying the assumption that it is calcite, and that there is about 29 wt. % calcium. This is generated by the carbonation of the lime in the atmosphere, which is the main strengthening process in historic lime mortars, $\text{Ca}(\text{OH})_2$ to CaCO_3 .

Calcium Silicate Hydrate (C-S-H) phases were localised as amorphous gel-like regions identified as C-S-H phases were observed in the microstructure. The significant SiO_2 and Al_2O_3 content (>50% combined) is associated with EDX, indicating limited pozzolanic reactions. This indicates partial hydraulic behaviour, possibly due to clay impurities or brick dust additives. The quartz grains are dense, angular, smooth-surfaced and low-porosity occurring in grains. Silicate-based

aggregates contain a high amount of silicon and aluminium. These aggregates are used for imparting mechanical stability and may also form a poor bond with the lime binding material.

The matrix is dominated by a well-developed interconnected pore network throughout it. These voids will help to improve vapour permeability but will also raise the water and salt ingress risks. If microcracks are present at the binder-aggregate interfaces, it means that degradation has occurred over time from environmental stress. These observations correspond with the previous research on lime mortars, which showed that the typical characteristics of long-term degradation of historic masonry systems are porosity and the failure of bonding [8, 10, 11].

4.1.4. Moisture Content and Hygroscopic Behaviour (Water Absorption Test)

The oven drying method (conventional) for moisture content determination, as shown in Figure 13, was used to assess the hygroscopic behaviour of the dome mortar (Figure 13). The mass of the container and the sample before drying was measured as 117 g. The mass after oven drying for 24 hrs at 105 °C was 117 g, which revealed no mass loss during drying. The moisture content (MC) was determined by making use of a typical relationship:

$$\text{Moisture Content (\%)} = (\text{Initial Weight} - \text{Dry Weight} / \text{Dry Weight}) \times 100$$

Substituting the measured values:

$$\text{Moisture Content (\%)} = (117 - 117 / 117) \times 100 = 0\%$$

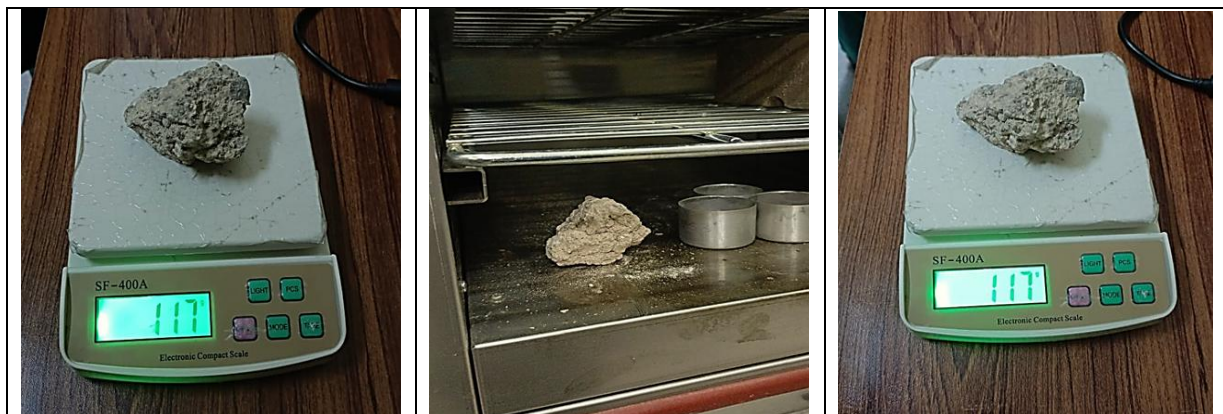


Figure 10. Moisture content test of mortar sample: (a) Initial weighing of the sample, (b) Oven-drying at 105 °C, (c) Final weighing after drying.

The analysed mortar sample therefore exhibited an approximate 0% moisture content under laboratory drying conditions. This result indicates that the specimen reached complete dryness after controlled oven exposure. It is important to note that a zero moisture value does not imply that the historic mortar is non-porous. Instead, the result confirms that both free and loosely bound water were removed during oven drying. Historic lime mortars typically store moisture within a network of capillary pores, which release water at elevated temperatures. Consequently, the findings suggest low retained moisture in controlled dry conditions but a high potential for water absorption under natural environmental exposure, which is consistent with the known hygroscopic and vapour-permeable nature of porous lime-based mortars [12, 13].

Integrated Material Interpretation

The findings of XRF, SEM-EDX, FTIR and moisture analysis confirm that the historic mortar is a non-hydraulic lime-based composite with a calcite binder and siliceous aggregates (Table 4). It has a high degree of porosity, poor interfacial adhesion, and microstructural variability.

The properties are typical of historic construction mortars, which were designed to be permeable, flexible and not rigid. But the same characteristics also render the material susceptible to deterioration, especially under humid and saline conditions. The small amount of partial hydrates (C-S-H) suggests the likelihood of pozzolanic reactions, likely due to naturally occurring contaminants or local materials. This indicates that it is a weak hydraulic system or not all air lime.

The Ali Mardan Khan Tomb shares common traits with other heritage sites, such as the Amfissa Cathedral, and shows some local differences [8, 55]. The binders in all cases are lime, but there are differences in the type of additives used and in the way the microstructural development proceeds. The sample in question does not contain any fibre reinforcement, whereas other Mediterranean mortars report that fibrous additives are present and that the mortars are hydraulically active. This means that the use of local resources and traditional Mughal building techniques. This agrees with the research conducted on other Lahore heritage structures with lesser modification of their lime-based mortars in colonial and Mughal structures. This is parallel with the research carried out on other heritage buildings of Lahore in colonial and Mughal buildings using limited modification in lime-based mortars [19]. The comparison shows the influence of local materials and traditional construction practices on mortar performance.

Table 4. Material Characteristics of the Tomb of Ali Mardan

Category	Feature	Key Observations	Significance
Material Composition (Tests)	XRF	High Si, Ca, K; lime-silicate mortar composition	Confirms lime-based historic mortar
	SEM-EDX	Calcite binder, C-S-H gel, silicate aggregates, porosity	Evidence of carbonation and hydraulic reactions
	FTIR	Carbonate, hydroxyl and silicate functional groups	Supports lime mortar identification
	Moisture Test	Very low moisture content	Indicates dry but porous material

Conservation Implications

A solid scientific foundation for creating appropriate repair mortars is provided by the comprehensive analysis. The silicate aggregate structure, high porosity, and lime-rich chemistry suggest that any repair material must:

- Maintain vapour permeability
- Match calcium carbonate chemistry
- Avoid cementitious stiffness
- Replicate pore structure and aggregate grading

These requirements justify the selection of Natural Hydraulic Lime (NHL)-based repair mortars, ensuring both compatibility and improved durability for conservation interventions [7, 8].

5. Integrated Interpretation and Conservation Implications

5.1. Integration of Architectural and Material Data

The overall architectural survey and laboratory investigations have given an integrated insight into the construction system of the Tomb of Ali Mardan Khan (Figure 14). Based on architectural documentation, it was determined that the monument was a double dome Mughal funerary structure featuring an elevated drum, chattris and octagonal plan. The survey also showed that the surface finishes were missing, the plaster surfaces were being eroded by various factors, and signs of mismatched repairs were found, which is in line with the trend of deterioration in Mughal heritage buildings [56, 57].

Material characterisation shows that the original construction used mortars containing a high amount of calcium and siliceous aggregates and had a rather porous internal structure, with low amounts of hydraulic phases. By reading this in conjunction with the architectural evidence, it is clear that the monument was conceived as a permeable masonry system, requiring the movement of moisture and vapour to be able to endure its passage in time [2, 58].

The combination of the two datasets shows a clear correlation between the original material choice and architectural performance, indicating that the tomb's lime-based fabric's compatibility controls its structural and environmental behaviour.

Correlation Between Material Composition and Deterioration Patterns

Field observation showed that a large percentage of the plaster was found to be detached, powdered, cracked and colonised by biological growth. Such deterioration patterns are very similar to those obtained from laboratory analyses (XRF, FTIR, SEM-EDX analysis).

The SEM micrographs show that the material system displays high porosity, which was verified by mineralogical analysis using XRF and FTIR, suggesting that the material has been formulated to control moisture by evaporation [1, 59]. But the use of compact modern restoration materials has affected this moisture balance. As a result:

- In historic masonry, moisture is trapped within the structure.
- Internal stresses build up as salt crystallisation occurs
- Micro-cracking and surface detachment speed up

This degradation is thus not only a result of the passage of time but is also closely associated with the incompatibility of materials and environmental exposure, as evidenced by many examples in heritage masonry work based on lime [60-62].

Assessment of Material Performance and Compatibility

The original lime mortar demonstrates several performance characteristics typical of historic Mughal construction:

- High vapour permeability
- Moderate mechanical strength
- Good thermal compatibility with brick masonry
- Self-healing potential through carbonation

These properties confirm that the original material was well-suited to Lahore's climatic conditions. In contrast, later cement-based repairs exhibit higher stiffness and lower permeability, creating mechanical and hygrothermal incompatibility within the masonry system [2, 16]. This mismatch

highlights the critical function that compatibility plays in conservation treatments by hastening cracking, separation, and moisture accumulation.

Development of Conservation Implications

The integrated interpretation is a clear framework for making conservation decisions. The paper proves that preservation of Mughal masonry can be done effectively if it is based on scientific evidence and compatibility [58, 61]. The findings underpin the need for conservation to go beyond the visual aspects and implement material-informed approaches to intervention, reflecting the original construction technology. The methodology suggested in the presented work can be replicated as a model for conservation planning of Mughal and South Asian historic masonry.

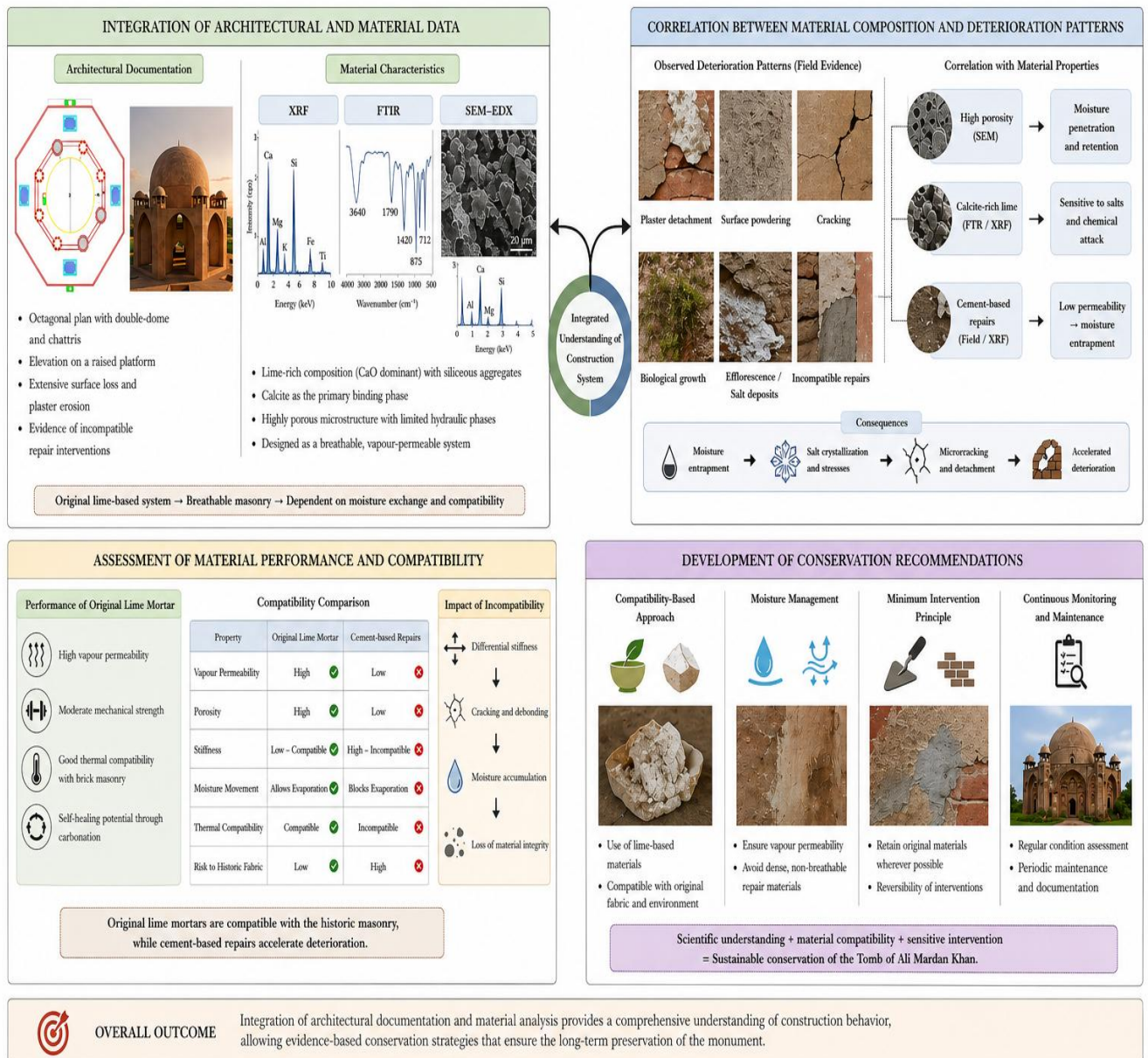


Figure 14. Integrated Interpretation and Conservation Implication

The microstructural and chemical characterisation results found in this study are associated with current research importance, the rank of material optimisation and performance assessment in maintainable construction materials [30-32]. The presence of calcium-rich binder times and silicate

aggregates indicates a comportment similar to lime-based and blended cementitious material studied in recent eco-concrete research. Limited pozzolanic reactions and high porosities coincide with the observations from LC3 and waste-based cementitious materials studies, where the interaction between the binder and aggregate plays an important contributing role to the durability and moisture transport [34, 63]. Under this point of view, the presence of these historical lime mortars also emphasises many similarities that confirm the statement that their conservation should not compromise their natural vapour permeability properties or their capacity for moisture exchange. In addition, the hygroscopic properties in the moisture content test were in line with investigations with the aim of developing porous construction materials and sustainable building systems [44, 64]. The industrial materials listed have been found to have low retained moisture levels in laboratory drying conditions and high moisture uptake values when exposed to the environment.

Linking material characterisation with architectural documentation enables a multidisciplinary approach that is reflected in the current research on the correlation of sustainability, construction management, and digital technologies, which can be incorporated into a conservation model [31, 35, 65-68]. This reinforces the importance of compatibility-based repair strategies for heritage structures.

6. Conclusion

This paper describes a complete set of physicochemical and microstructural analyses of historic lime mortar from the Ali Mardan Khan Tomb, Lahore, through a combined analytical technique involving X-ray Fluorescence (XRF), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM-EDX) and water absorption tests. The integrated findings offer a consistent picture of the composition, structure and degradation of the historic mortar.

The XRF results verified that the mortar comprises mainly silica- and calcium-rich components, with SiO₂ (42.39%) and CaO (21.96%) as the dominant oxides, suggesting a non-hydraulic lime mortar, with siliceous aggregates originating from natural sources. The FTIR analysis also confirmed the prevalence of calcite phases, confirming the long-term carbonation of lime as the main binder. SEM-EDX microstructural analysis showed a highly porous and irregularly shaped voids, angular quartz aggregates, and poor bonding between the binder and aggregates, suggesting significant weathering and environmental degradation. Moreover, the presence of minor C-S-H phases indicates minor hydraulic activity, likely due to impurities and/or local pozzolanic reactions.

Water absorption measurements confirmed the porous structure and moisture sensitivity, which are natural characteristics of traditional lime-based mortars, but also lead to long-term deterioration when exposed to environmental conditions. Overall, these results confirm that the original mortar is a highly porous, lime-based composite material that is breathable and compatible, but not stiff.

The research also shows that the observed deterioration processes of the monument are related to environmental conditions, material ageing and the incompatibility of the modern repair mortars. These have substantially changed the integrity and behaviour of the historic masonry system. The holistic analytical methodology employed in this study offers a sound scientific foundation for the study of historic mortars and provides key insights for conservation. This research demonstrates that the long-term stability of Mughal masonry relies on maintaining material compatibility, vapour permeability and moisture balance within the building fabric. The integrated methodology developed in this study provides a replicable conservation framework for historic masonry across South Asia and comparable climatic regions.

7. Recommendations

The results of this research have provided some useful and evidence-based guidance for conservation and future studies of historic lime mortars.

- Conservators should consider using suitable lime mortars (such as NHL or air lime systems) instead of cement mortars to avoid mechanical and chemical incompatibilities with historic materials.
- Site-specific material analysis (using XRF, FTIR, SEM-EDX and water absorption measurements) should be conducted before conservation to inform scientifically based practice.
- Repair mortars should be formulated to have similar properties to the original material, in terms of porosity, permeability and aggregate sizing to ensure structural and hygric compatibility within the masonry system.
- Appropriate water management, such as enhancing drainage and controlling rising damp, should be adopted to mitigate water-driven deterioration.
- Use of cement-based or too stiff mortars should be avoided as they limit vapour diffusion and lead to deterioration of historic materials.
- Routine monitoring and condition surveys should be conducted to monitor deterioration mechanisms such as crack development, salt attacks and mortar degradation.
- Future efforts should include building a regional historic mortar database, which can be used as a guide for standardised but flexible conservation practices for other similar historic buildings.

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