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MATERIAL CHARACTERISATION AND CONDITION ASSESSMENT OF HISTORIC WALL MORTAR AT POONCH HOUSE, LAHORE-PAKISTAN: IMPLICATIONS FOR COMPATIBLE CONSERVATION

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ABSTRACT
Poonch house is a late nineteenth-century colonial house in Lahore, Pakistan, and it is a very important but decaying specimen of hybrid Indo-European architecture. Its cloth has been subject to a series of declines bearing the effects of moisture, salt crystallisation and unsuitable replacement of lime mortars by Portland cement. This research is a thorough description of the original wall mortar so as to embark on coherent conservation measures. Scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) was applicable to the representative samples to identify the various elevations and exposure conditions under investigation and analyse the data in order to establish the gravimetric moisture determination, X-ray diffraction (XRD), and in-situ ultrasonic pulse velocity (UPV) testing. The findings prove the presence of a lime-rich binder featuring and aluminous aggregate with broken brand pieces of bricks, which shows that there is a historical non-hydraulic lime

mortar. SEM micrographs showed the existence of a porous and heterogeneous matrix with clear and specific grain boundaries and microcracking, and EDX spectra indicated trace salt contamination, as well as chlorine is siliceouspresent. According to XRD analysis, calcite, quartz, gypsum, and halite were the main mineral phases, as it is evidenced by carbonation, sulfate attack and salt crystallisation. The moisture content (mean of 8.77 percent) is low (less than 1.0 km/s in degraded regions), and thus, indicates that there is high microstructural weakening in the moisture-exposed regions. The aforementioned combination of microstructural, chemical, and non-destructive diagnostics can be presented as an evidence-based approach to the choice of compatible lime-based repair mortars and control over the deterioration caused by moisture. This study will add a regional model of scientific evaluation and conservation of South Asian colonial masonry heritage.

Keywords: historic lime mortar; SEM–EDX; XRD; ultrasonic pulse velocity; salt deterioration; heritage conservation; Poonch House, Lahore.

1 INTRODUCTION

One of the most architecturally and historically important colonial-era houses that remain in the area is Poonch House, which stands along Multan Road in the Mozang region of Lahore, Pakistan. The building was built in the late nineteenth century on commission by the Maharaja of Poonch, a prince of the colonial social and material structures in the north-western regions of the Himalayas, and observed the neighbours in terms of cultural and functional hybridity of the South Asian colonial buildings. The building was a ceremonial and residential estate that integrated the European Neoclassical ideals, such as the massing with a centralised focus, columnedity of masonry bases and techniques of window arches, with the local construction traditions ideology, i.e., the use of bricks and lime. The solid brick masonry that it used was combined with air lime mortar that was enhanced by lime plaster and moulded stucco ornamentation, which reflected climatic adaptation as well as shifting technologies between local masons and colonial engineers.

After the resettlement of the subcontinent politically in the year 1947, Poonch House became a state property under the Government of Pakistan. It was later used as state offices, diplomatic receptions and assembly gatherings in future decades. The photographs and historical accounts of the construction reveal that the building was constructed in the middle of the twentieth century in good condition, and it has very slight weathering of the lime plaster and facade integrity. Nevertheless, subsequent works, principally the substitution of initial mortars made of lime with Portland cement and the screeding of impermeable surfaces, have badly perturbed the hygrothermal equilibrium of the building. The incompatibility of these materials, in addition to the lack of systematic care, results in moisture retention, salt crystallisation and disintegration of the original fabric to granules.

2 Environmental and Urban Context

These decay mechanisms are worsened by the climatic conditions of Lahore. The climate in the city is semi-arid and humid subtropical in nature (Abbas et al., 2023), with the temperatures going as high as 40 ^{o}C in summer (Zia, 2014), rains of more than 200 mm per month (Monsoon) and the relative humidity ranging between 35-85 percent among seasons (Shirazi et al., 2019). One of the effects of such variations is that they lead to repeated cycles of wetting and drying, which hasten the crystallisation of soluble salts in the porous mortar structure. Moreover, the location on Multan Road is exposed to excessive vehicular emissions, which expose the facades of the building to elevated levels of SO2, NOx, and dirt ("<Emission Inventory of Lahore 2023.pdf>,"). They facilitate the conversion of lime binder to gypsum crusts, which minimise the permeability to the vapour and cause the existence of the lateral and different stresses between surface and substrate layers. Lack of drainage on the site and the capillary contact of the groundwater worsen the damp ascending along the lower courses of the building (Proietti et al., 2021), and the fact that the roof maintenance is insufficient adds to direct water migration

("<editor_in_chief,+EJERS_2598.pdf>,"). Collectively, these environmental and human-influenced issues have continued to affect the integrity of the masonry system.

3 Significance of Lime Mortars in Heritage Masonry

Historic mortars of lime dominate a central position within the performance and authenticity of the traditional masonry buildings. The high vapour permeability, low modulus of elasticity, combined with the ability to self-heal as a result of continuous carbonation (Elert et al., 2002), give them the perfect fit to the dynamic environmental conditions of South Asia. Most commonly used during the period of colonial rule were non-hydraulic air lime mortars, which were normally of a lime putty and locally available siliceous sand because of their workability and their ability to fuse with the brick masonry (Morris, 2024). At times, a pozzolanic material was added, crushing the pieces of crushed bricks so that they could speed the setting process and also withstand moisture. Nevertheless, such mortars rely on open porosity to be effective. During extended exposure to contaminants and prolonged moistness, the chemical changes, i.e. formation of gypsum and halite, occur, defining the weakened binder-aggregate bond (Schueremans et al., 2011). In addition, the balance of vapours has been altered with the introduction of Portland cement during repair campaigns in the twentieth century and has brought about mechanical incompatibility and fast decay at the interface of the new finishing and the old finishing (Gulotta et al., 2013).

In a conservation perspective, the physicochemical properties of historic lime mortars are significant knowledge on material compatibility in conservation. The principle of evidence-based intervention supported by laboratory characterisation and not empirical substitution, which is stressed in international guidelines, such as the Venice Charter (1964) and ICOMOS principles of compatible repair (Al-Barzngy & Khayat, 2023; Icomos, 1964), insists on the sufficient compatibility of interventions. However, conservation practice in Pakistan, as in a large part of South Asia, is largely descriptive, based on one's eye or familiar repair material, without sufficient scientific examination.

4 State of Research and Knowledge Gap

Within the last twenty years, the science of heritage conservation has changed due to the development of materials characterisation. Both scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM–EDX), X-ray diffraction (XRD) and ultrasonic pulse velocity (UPV) studies have been an invaluable method in determining microstructural morphology, mineralologic composition, and internal cohesion of historic mortars (Jonaitis et al., 2018; Liritzis et al., 2015). In other studies reveal the effect of mineralogical composition and pore structure on the durability under the site-specific climatic regimes (Franceschini et al., 2024; Liritzis et al., 2015; Uygunoğlu et al., 2019). Similar literature show that vegetal fibres are used to enhance tensile strength in lime-based mortars (Quintaliani et al., 2022), and one more study provided information on how saline aerosols can accelerate the lime breakdown in coastal area (Castañeda et al., 2018).

Conversely, comprehensive scientific investigations of South Asian colonial masonry are rather limited. Numerous studies of historic edifices in Lahore (e.g., Gulzar et al., Nur Jahan; masonry assessments of Shish Mahal and Lahore Fort) and regional surveys in northern India have predominantly employed chemical spot tests, optical microscopy, and basic mineralogical analysis, rather than comprehensive multi-analytical methodologies (Saima Gulzar, Muhammad Nawaz Chaudhry, et al., 2014; Kabir et al., 2024; Kamran & Awan, 2015). Comprehensive investigations integrating SEM–EDX, XRD, quantitative moisture profiling, and ultrasonic pulse velocity (UPV) are scarce, hindering the compilation of robust reference datasets for developing compatible lime-based repair mortars and fully understanding the impact of the warm, polluted South-Asian climate on long-term masonry performance (Saima Gulzar, Muhammad Nawaz Chaudhry, et al., 2014).

5 Case Study Justification: Poonch House

Poonch House, located along Multan Road in the Mozang area of Lahore (31.5540° N, 3 74.3148° E) was chosen (Figure 1) been chosen as a case study due to the typology of the building, as a result of its architectural structure and also because of the conservation issues that it represents. It is surrounded by architectural features, and it is one of the few surviving princely residences in Lahore that are still standing with colonial construction of masonry that has not been altered in its original plan or elevation. Combining a neoclassical shape with native craftsmanship is typical of the general trend of hybrid colonial buildings in South Asia (Figure 2). Conservatively, it offers a distinct chance to study the processes of deterioration in a non-hydraulic lime system in a compact, polluted urban area - the circumstances that characterise a large number of heritage buildings being endangered in the area (Figure 3).

Additionally, Poonch House has been registered as a protected provincial heritage site under the provincial heritage insurance policies, material analysis and its own regeneration plan are yet to be executed. Knowledge of its mortar composition, microstructure and degradation mechanisms, therefore, may provide a scientific rationale for evidence-based restoration of this building as well as more colonial complexes, including the Shadi Lal Building and the heritage blocks of the Aitchison College. Therefore, the research of Poonch House is performed, at the same time, both as a local diagnostic practice and a regional prototype of the evaluation of heritage materials.

Figure 1. Location of Poonch House, Lahore

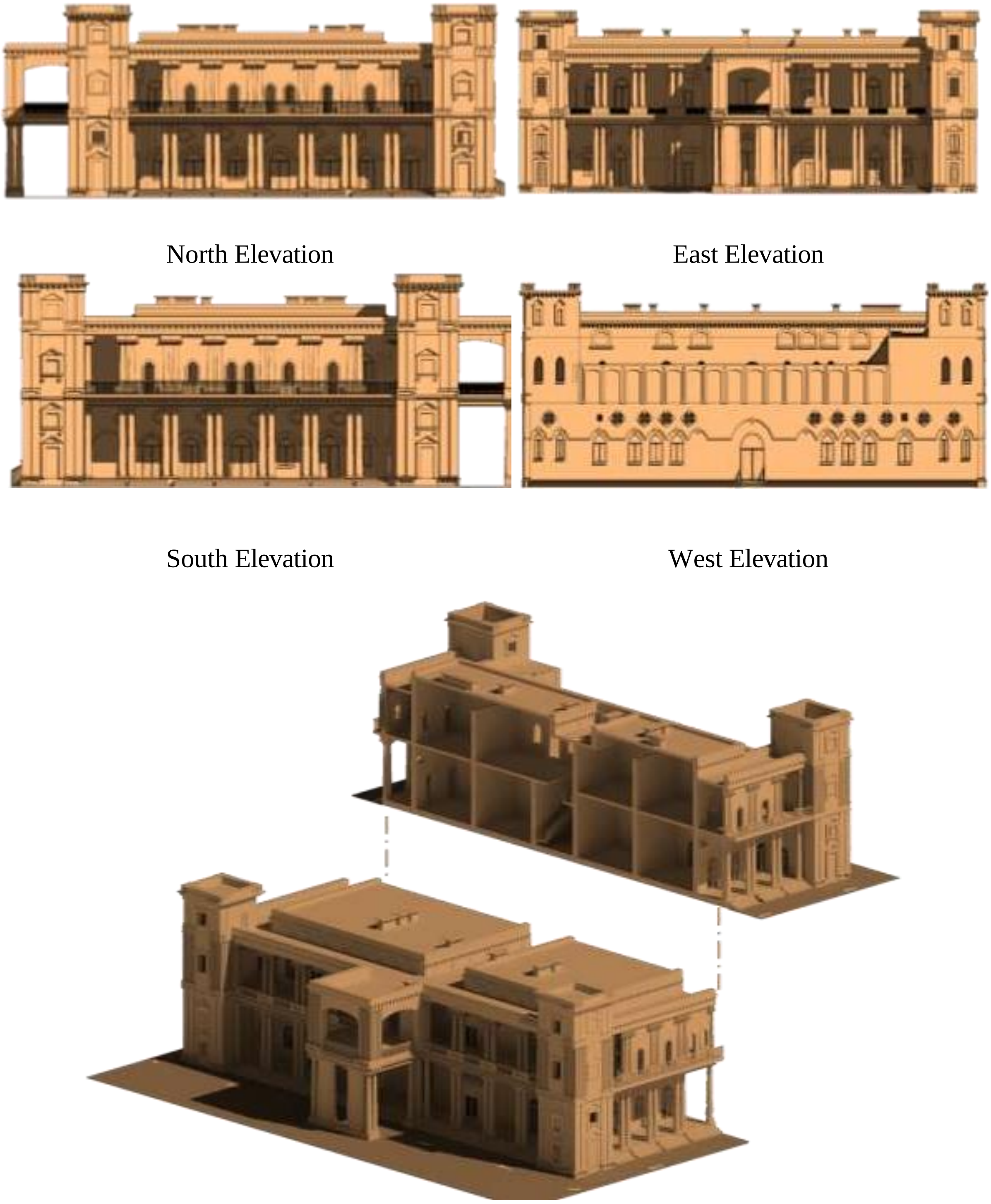

Figure 2. Elevations and 3D sectional view, Poonch House, Lahore

Figure 3. Few deteriorated spots observed on the façade and walls of Poonch House, Lahore.

6 Research Objectives and Contribution

The present study aims to advance scientific understanding of colonial-period lime mortars in South Asia through a comprehensive characterisation of the wall mortar at Poonch House, Lahore. The specific objectives are to:

1. Characterise the binder–aggregate composition and microstructural features of the original mortar using SEM–EDX and XRD analyses;
2. Evaluate the moisture behaviour and internal cohesion of the material through gravimetric and ultrasonic pulse velocity (UPV) testing;
3. Identify the dominant deterioration mechanisms associated with environmental exposure and incompatible repair interventions; and
4. Develop recommendations for the formulation of compatible lime-based repair mortars and preventive conservation strategies.

Incorporating both the destructive and non-destructive diagnostic methodology, this study will not only help provide empirical evidence but also provide a methodology that can be implemented into its conservation in the humid subtropical and polluted urban areas. It is predicted that the outcomes would facilitate the use of material compatibility parameters in restoration, it would assist the authorities in conservation in Pakistan to generate procedures in conservation maintenance, and raise the bodies of conservation science literature in the region.

7 Materials and Methods

8 Study Site and Sampling Strategy

Poonch House was chosen as a case in point of masonry at the place of application of non-hydraulic lime mortar in colonial times. The sampling exercise was aimed at detecting spatial differences in material composition and degradation. Mortar sample size of twelve specimens (six interior and six exterior) joints at different levels and orientations were taken to include the influence of environmental exposure, upkeep of moisture and also the earlier interventions.

The sampling points (Figure 4) were placed on the evident deterioration characteristics (cracking, spalling, efflorescence, or cementitious over-repairs). One sample (30-50g) each was removed with a chisel and hammer in order to control surface contamination and structural damage as much as possible. Samples were put under airtight polyethene and labelled with their exact location and position, and taken to the conservation materials laboratory to be analysed in controlled humidity conditions (40-45% RH). Anything mercantile in the field existed under the authorities of the provincial heritage authority, approval and supervision.

Figure 4. Sampling of deteriorated wall mortar for laboratory analysis

2.2. Laboratory Analytical Framework

The analytical framework combined microstructural, chemical, and non-destructive techniques to characterise the original mortar composition and assess its physical integrity. The workflow comprised:

1. Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM–EDX) for microstructural and elemental analysis;
2. X-ray Diffraction (XRD) for mineral phase identification;
3. Gravimetric moisture determination to quantify hygroscopic behaviour; and
4. In-situ Ultrasonic Pulse Velocity (UPV) testing to evaluate internal cohesion and detect heterogeneity.
5. This multi-method approach allowed a holistic interpretation of the material's condition, correlating microstructural, compositional, and mechanical data.

9 Scanning Electron Microscopy and Energy-Dispersive X-ray Spectroscopy (SEM–EDX)

Fragments of mortar were carefully scraped of loose material and attached to aluminium stubs by use of conductive carbon tapes. Samples were then coated with gold to a thickness of about 10 nm in order to make samples conductive. Scanning was performed using a JEOL JSM-IT200 scanning electron microscope, which operated at an accelerating voltage of 15-20 kV and a working distance of 10-15 mm in backscattered electron (BSE) mode in order to distinguish between binder and aggregate phases on the basis of atomic number contrast.

The experiment was analysed by elemental analysis with an Oxford Instruments EDX attached to the SEM, and the quantitative analysis of the results was made with ZAF to provide the elemental results. Spectra were looked at in each sample at least three points, and the data are shown in normalised percentages of the atoms (mean ± SD). Major elements such as: Ca, Si, Al, Fe, K, Mg and minor elements such as Na, Cl, S were also determined to determine the composition of the binder and the type of aggregate used and possible salt contamination. SEM-EDX outcome provided a useful insight into the binder-aggregate interface and the secondary phases present in connection with environmental change (Stefanidou & Pavlidou, 2018).

10 X-ray Diffraction (XRD) Analysis

Mineralogical identification was done through a Bruker D8 Advance diffractometer, which uses Cu Kα radiation (λ = 1.5406 Å) at a standard of 40 kV and 40 mA. Homogeneity was ensured because samples were sieved and crushed to less than 75 µm. The data were recorded at a 2θ range of 5 to 70 degrees and with a step size of 0.02 degrees and within a counting time of 1s/step (S. Gulzar et al., 2014).

Identification of the phase was conducted by the use of the ICDD PDF-4 database, and relative intensity of major crystal components was made in comparison with each other to assess the abundance of major crystalline components. It was interpreted using diagnostic reflections of calcite ($CaCO_3$), quartz (SiO_2), gypsum ($CaSO_4 \cdot 2H_2O$) and halite (NaCl). The EDX results were supported by the XRD results, which confirmed the original material properties as well as secondary altered products.

11 Gravimetric Moisture Content Determination

Moisture content was determined according to ASTM D2216-19 (Astm, 2010), adapted for historic masonry mortars. Each specimen was weighed to obtain the wet mass ($W_{(wet)}$), oven-dried at 105 ± 5 °C to constant mass ($W_{(dry)}$), and reweighed after cooling in a desiccator (Astm, 2010). The moisture content (MC) was calculated as;

Three replicates were compared at the location, and the results are given in the form of mean SD. Such a

$$\text{Water Absorption (\%)} = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100$$

procedure measured the hygroscopic action of mortar and allowed correlating the identified phenomenon with the actual occurrence of efflorescence and crystallisation of salts. Areas that had MC 8 percent or more were termed as those at high risk of active salt cycling, as suggested by Hall and Hoff (Hall & Hoff, 2021).

12 Ultrasonic Pulse Velocity (UPV) Testing

Meanings of in-situ UVP were made in compliance with ASTM C597-16 (Astm, 2016), using a Proceq Pundit Lab+ portable ultrasonic tester with 54 kHz transducers (Miturski et al., 2021). Direct and semi-direct, and indirect transmission arrangements were utilised on the basis of accessibility. The acoustic contact between the probes and the surface of the mortar was to be conducted using coupling gel. For each measurement, the path length (L) and travel time (t) were recorded, and the pulse velocity (V) was calculated as

$$V = L/t$$

Three readings were made and measured at an average per location. According to the available literature, any velocity exceeding 3.0 km/s would refer to dense and coherent materials, and any value less than 1.0 km/s would represent highly porous or fractured areas. The spatial pattern of velocities was subsequently mapped to determine areas which had changed in internal cohesion, as well as areas where snap-on conservation actions were needed.

13 2.7. Data Integration and Interpretation

Results obtained from SEM-EDX, XRD, moisture analysis and UPV tests have been synthesised to provide an understanding of the behaviour of multi-scalar mortar. Because of the correlation between the wall microstructural properties, salt concentration, and UPV, the wall sections were classified into three groups:

a) Intact (dense, well-carbonated limestone, slight micro-cracking)
b) Moderately degraded (increased moisture, sizeable loss of cohesion).
c) Severe degradation (microcracking, dewatering, salination);

These categories were used for further discussion of the mechanisms of deterioration as well as for explaining conservation recommendations. All analyses were undertaken according to principles of conservation ethics, which raise the principle that excess intervention should be avoided and the original fabric should be preserved.

3. RESULTS:

14 Microstructural and Compositional Analysis

SEM analysis showed that the microstructure is heterogeneous in all the mortar samples from Poonch House (Figure 5-7). The binder phase was characterised by the numerous fine angular particles typical of air lime carbonation, between which there were coarser siliceous and aluminous aggregates, quartz grains and fragments of siliceous, compressional shingles. The aggregate-binder interfaces were, in general, irregular with part debonding and microcrack propagation, as was especially significant for samples from exposed facades. The capillary action is consequently improved by the presence of elongated voids and interconnected pore channels that are most probably the conductive transport mechanism for moisture and salt diffusive transport in the mortar matrix. Backscattered electron (BSE) images showed various secondary mineral depositional areas of recrystallised gypsum and halite in the cracks and pore throats. The shape of these deposits (needle-like and prismatic crystals) is in favour of the interpretation of salt-induced accumulation of mechanical stress due to cyclic wetting and drying. EDX spectra showed the composition of a lime-rich binder with Ca, Si, Al and less Fe, K and Mg. Trace sodium (Na) and chlorine (Cl) peaks were observed in several samples, pointing to the contaminant of chloride. Different intensities of Na and Cl in the sampling area are proportional to different exposure degrees to moisture ingress and environmental pollution.

Element	Weight%	Atomic%
O	59.76	73.92
Na	0.59	0.51
Mg	0.86	0.70
Al	10.01	7.34
Si	16.70	11.77
Cl	0.33	0.19
K	3.65	1.85
Ca	6.18	3.05
Fe	1.92	0.68
Totals	100.00	

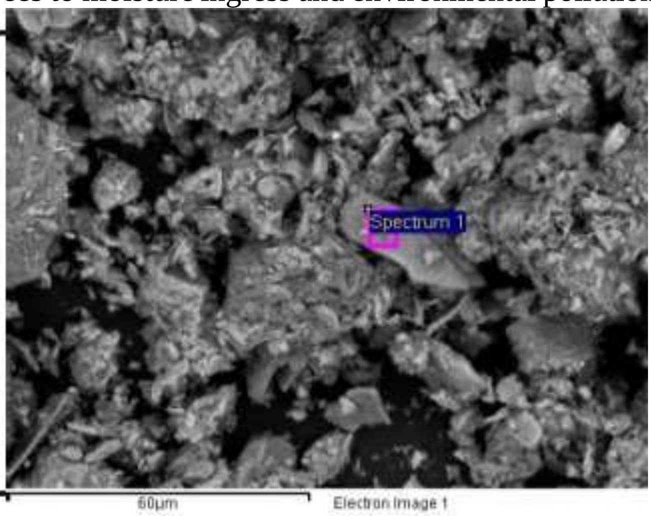

Figure 5. SEM Analysis of Sample 1

Element	Weight%	Atomic%
C	15.19	22.79
O	53.72	60.51
Na	0.51	0.40
Mg	1.32	0.98
Al	3.89	2.60
Si	9.66	6.20
Cl	0.22	0.11
K	0.77	0.36
Ca	10.30	4.63
Fe	4.42	1.43
Totals	100.00	

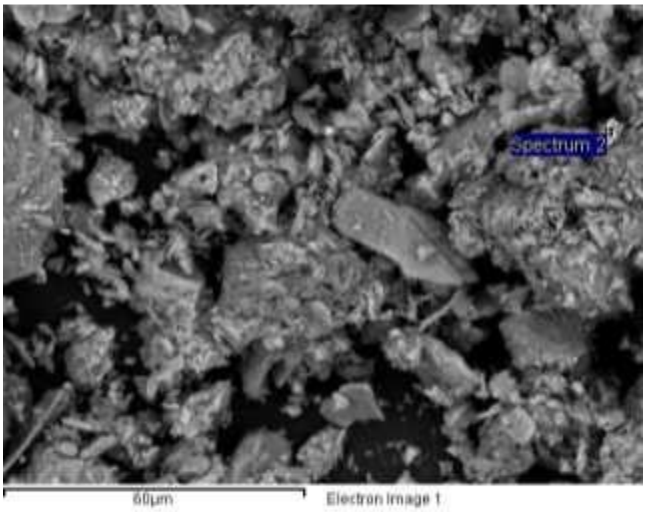

Figure 6. SEM Analysis of Sample 2

Element	Weight%	Atomic%
C	17.71	26.34
O	49.43	55.21
Na	0.90	0.70
Mg	0.92	0.68
Al	3.74	2.48
Si	14.05	8.94
K	0.57	0.26
Ca	10.64	4.74
Fe	2.03	0.65
Totals	100.00	

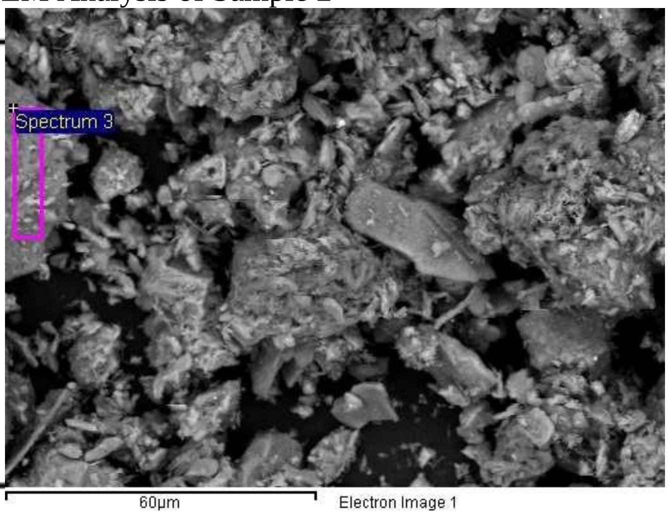

Figure 7. SEM Analysis of Sample 3

A summary of the major elemental compositions is provided in Table 1, illustrating the predominance of calcitic lime and siliceous aggregates with minor contaminants.

Table 1. Representative elemental composition of historic wall mortar (mean atomic% ± SD).

Sample ID	Ca	Si	Al	Fe	Mg	K	Na	Cl	Interpretation
S1 (Interior)	35.7 ± 0.4	16.2 ± 0.3	8.9 ± 0.5	2.1 ± 0.2	1.2 ± 0.1	1.0 ± 0.1	—	—	Well-carbonated lime with a stable interface
S2 (Exterior, south facade)	32.9 ± 0.5	18.1 ± 0.4	9.6 ± 0.3	2.3 ± 0.2	1.4 ± 0.2	1.1 ± 0.1	0.9 ± 0.1	0.6 ± 0.1	Salt-affected, moderate chloride contamination
S3 (Arch zone)	30.8 ± 0.6	19.0 ± 0.5	10.2 ± 0.4	2.4 ± 0.2	1.3 ± 0.1	1.2 ± 0.1	1.1 ± 0.1	0.8 ± 0.1	High porosity and salt enrichment

S4 (Interior parapet)	34.5 ± 0.3	17.3 ± 0.4	8.5 ± 0.4	2.0 ± 0.2	1.2 ± 0.1	1.0 ± 0.1	—	—	Intact, well-bonded microstructure

The elemental distribution confirms that the mortar is non-hydraulic air lime with minor pozzolanic contribution from crushed brick inclusions. Samples with elevated Na and Cl correlate with visible efflorescence, reinforcing the link between environmental exposure and salt migration.

3.2. X-ray Diffraction (XRD) Analysis

The characteristic peaks, which are due to the binder and the aggregate phases, can be identified in the obtained XRD patterns of representative samples (Table 2). The most abundant crystalline components are calcite ($CaCO_3$) and quartz (SiO_2), which stand for carbonated lime binder and siliceous aggregate, respectively. Several samples from the exterior were selected for further alteration studies, and secondary peaks for gypsum ($CaSO_4.2H_2O$) and halite (NaCl) were recorded, indicating post-depositional alteration processes have taken place. The gypsum formation indicates sulfation of the lime binder and most probably resulted from reaction with atmospheric SO_2 and particulate air pollutants. Halite formation, on the other hand, is indicative of salt in-migration and precipitation as a result of moisture cycles, and possible rising damp.

Weak reflexes between 40–50° 2θ indicate weakly crystalline or amorphous phases, which may be associated with secondary carbonated phases or fly ash unreacted agglomerated lime (Figure 8). Laterite, therefore, follows the idea of the originally non-hydraulic composition of the mortar, in the absence of hydrated phases such as belite or aluminates.

Table 2. Principal mineral phases identified by XRD.

Mineral	Chemical Formula	Origin	Interpretation
Calcite	$CaCO_3$	Carbonated lime binder	Primary binder phase
Quartz	SiO_2	Sand and crushed brick aggregate	Stable inert component
Gypsum	$CaSO_4·2H_2O$	Reaction product of lime with SO_2	Sulfation and crust formation
Halite	NaCl	Soluble salt from moisture ingress	Salt crystallisation damage

The combination of calcite, quartz, gypsum, and halite indicates both original compositional features and secondary deterioration mechanisms, aligning with the microstructural observations from SEM-EDX.

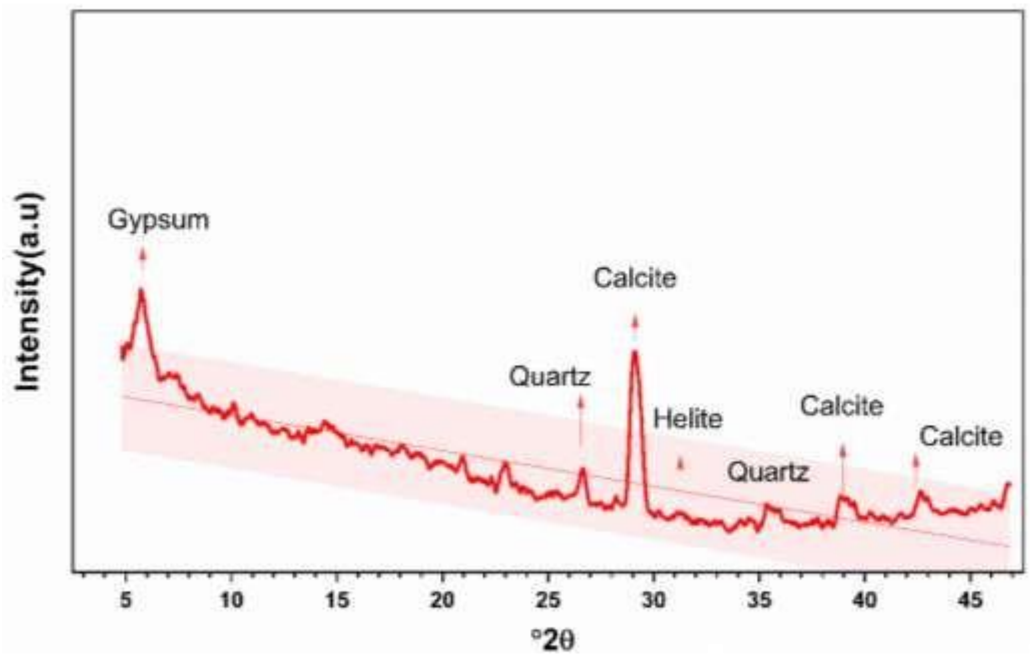

Figure 8. XRD diffractogram of the historic wall mortar (Sample 3). The major peaks correspond to calcite and quartz, confirming a lime–sand composition. Minor peaks indicate gypsum and halite.

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16 **Moisture Content Test**

Gravimetric analysis found measurable differences in moisture content/Water absorption between certain of the sampled locations, showing the difference in exposure and permeability. With the discrepancies of samples, the total mean value of moisture content was 8.77 +- 0.62% or from 7.85% to 9.91% (Figure 9).

Samples from the south-facing facade had the highest moisture level (mean 9.41 %), the samples belonging to the places affected by rainfall runoff and defective roof drainage. By comparison, interior sections of walls showed lower values of water absorption (mean 8.12%). This spatial variation is brief evidence of the tremendous effect of orientation and microclimatic exposure on hygric behaviour. According to Hall and Hoff's (2007) threshold criteria, moisture contents higher than 8% are indicative of a high risk of active salt crystallisation. The high values noted here and the combination of the sodium and chlorine ions noted by EDX analysis indicate progression of moisture-driven degradation in exposed masonry sections.

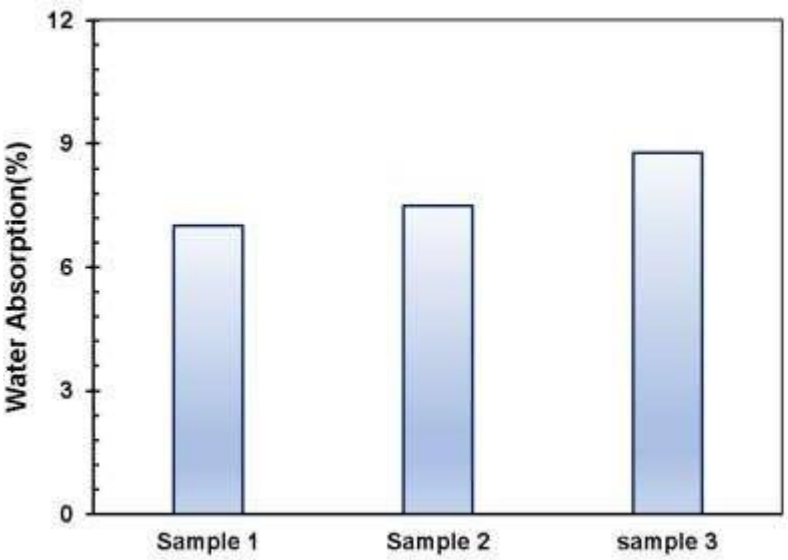

Figure 9. Spatial distribution of average Water absorption across sampled wall sections..

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18 **Ultrasonic Pulse Velocity (UPV) Test**

Ultrasonic testing indicated the internal cohesion and the structural integrity of the historic mortar, which was of great value for quantitative purposes. Recorded pulse velocities varied from 0.43 km/s to 1.75 km/s, with a mean of 1.48 km/s for all the measured locations. Higher velocities (>1.7 km/s) were associated with interior wall sections and indicate dense and well-carbonated lime with a small amount of voids. Moderate velocities (1.1-1.4 km/s) were observed in transitional areas, which were semi-exposed and associated with partial loss of the bonding and higher porosity. In arch segments and parapets, the speeds (below 0.8 km/s) were the lowest, and it was also observed by visual monitoring that very advanced microcracking and granular disintegration occurred.

The obtained results (Figure 10) reveal high spatial correlation between environmental exposure and internal degradation: in places with higher content of moisture and salt, the pulse velocities are obviously reduced. These values confirm a significant loss of internal cohesion and, compared with the published reference raw material and corresponding intact historic lime mortar (2.0-3.0 km/s), these values can be interpreted as milder dilation of the general structure (Moropoulou et al., 2005; Robbiola & Portier, 2006). The UPV findings therefore prove the progressive weakening of the mortar matrix even without visible damage (areas especially in the presence of moisture).

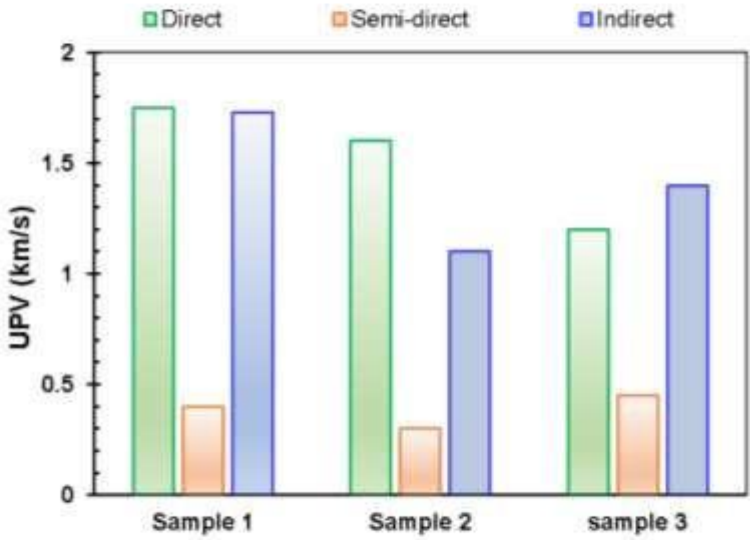

Figure 10. UPV Results of Wall Mortar

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20 Integrated Interpretation

The results from SEM-EDX, XRD, gravimetric moisture analysis, and UPV experiments, for the mortar used as the external support of the Poonch House, allow researchers to describe a coherent picture of the material composition, deterioration mechanism and internal structure behaviour of the wall mortar. Taken together, the data confirm that the original binder was a non-hydraulic rendering air lime mixed with siliceous sand and small inclusions of crushed brick, which was a common recipe from the later nineteenth-century colonial masonry of the Punjab area. Although these mortars were regarded as an asset because of their merits of permeability and microstructural flexibility, today it is their same openings that make them extremely vulnerable to the adverse effects of moisture and salt due to climatic and pollution conditions prevailing in Lahore.

3.4.1. Microstructural-Chemical Interactions

SEM and EDX analyses showed that the binder-aggregate of the mortar interface is moderately cohesive with weakened microcracks and void networks. These discontinuities act as pathways for capillary transport for the movement of moisture and soluble salts through the fabric. The appearance of sodium and chlorine peaks in several samples and the presence of secondary crystalline deposits are proof that salts containing chlorine have invaded the matrix. The micrographs reveal acicular and prismatic crystals typical of halite and gypsum, which indicate alternating cycles of dissolving salt and recrystallising it. The XRD results support these conclusions, showing that calcite is the main binder phase and quartz is the main aggregate component, as well as secondary gypsum and halite phases. The fact that gypsum is formed by reacting lime ($CaCO_3$) and atmospheric SO_2 is an illustration that this is a typical reaction in urban heritage environments, in other words, that the formation of gypsum is the result of a kind of chemical transformation, a chemical ligation, in this case, that is caused by pollution (Charola, 2000). This simultaneous appearance of halite indicates that the metabolite exhibition of chloride ingress is probably due to the rising damp and destruction from pollinated aerosols, leading to further crystallisation pressures. These coupled chemical processes cause progressive widening of microcracks already existing, reduction of effective contact between binder and aggregate, and increased porosity.

3.4.2. Moisture Dynamics and Hygroscopic Behaviour

The average mortar moisture content of 8.77% found the mortar to be just under the critical moisture content of active salt cycles. Super saturation of moisture in south-facing and adjacent zones to the roof corresponds with the physical evidence of efflorescence (Figure 3) and subflorescence. This correlation stresses the fundamental role that moisture diffusion has, being the medium of the transport of the salts, as well as the mechanism of their phase transition. During wetting periods, soluble salts are mobilised and penetrate the pore network of mortar; during the drying period, they crystallise and cause expansive stress. Repeated cycles of crystallisation may produce pressures in excess of 20 MPa - more than enough to interfere with the tensile capacity of lime binders, which normally fall in the range of 0.2 to 1.0 MPa.

Thus, the occurrences of the three factors (high moisture content, microcracking, and chloride presence) together prove that hygroscopic and crystallisation stresses work synergistically to cause granular disintegration. This mechanism, which is in line with the deterioration mechanism seen in similar kinds of lime mortars from humid subtropical climates studies (Awan, 2016; Scherer, 2004; Tsirliganis et al., 2004).

3.4.3. Mechanical Response and Cohesion Variability

These microstructural and chemical interactions were quantitatively validated by a physical understanding of UPV testing at the macroscopic scale. The diameter of the measured velocities (0.43-1.75 km/s) suggests a considerable heterogeneity in the internal cohesion, with the minimum velocities spatially coinciding with areas with high moisture content and salt effect (Vasanelli et al., 2017; Vasanelli et al., 2015). Taking into account that intact lime mortars usually provide more than 2.5 km/s, the depressed values are an indication of a significant loss of elastic continuity. The direct relationship between low UPV values and cracking observed by SEM and high moisture content shows that the salt crystallisation and microstructural porosity have seriously damaged the load-bearing capacity of the material. Notably, even sections which look visually sound have moderate decreases in UPV, which implies the presence of subsurface deterioration (not apparent to the naked eye). The demonstration that a combination of non-destructive (UPV) and micro-analytical (SEM-EDX) methods is useful for locating hidden areas of decay before failure of the structural components.

3.4.4. Synthesis and Diagnostic Implications

Collectively, all the analyses provide a framework for moisture-salt-pollutant interaction as a component of the deterioration process for a non-hydraulic lime-bearing matrix in its vulnerable state. The porosity and permeability, which initially guaranteed the breathability of the mortar, now favour the intrusion of contaminants. The ensuing action of the sulfation and the salt crystallisation has led to a multi-phase degrading sequence:

1. Accumulation of pollutants → formation of gypsum crusts;
2. Moisture penetration to the salts → solubility and mobilisation;
3. Drying cycles → crystallisation and microcracking;
4. Loss of cohesion → mechanical weakening of the material detected by UPV.

This progression explains both the visible surface decay as well as the hidden structural decay experienced in the Poonch House masonry. The variance of chemical (EDX, XRD) and physical (UPV, moisture) indicator consistency is a good confirmation of the robustness of the interpretation. These insights are at the scientific base of specifying compatible lime-based repair mortars, ones replicating the original porosity and vapour permeability and resistant to pollutant-induced sulfation, and putting moisture management and salt mitigation as a central part of conservation action.

21 Discussion

22 Interpretation of Material Composition and Provenance

The obtained results support the state that the mortar of the Poonch House is a non-hydraulic lime-sand compound with low percentages of crushed brick admixture. This building is a product of the colonialist encounter of appropriating British masonry traditions in locally available materials in northern India and Pakistan in the late nineteenth century. Similar mortar compositions have been recorded in Indo-Saracenic edifices (Shuja & Junejo, 2020). The incorporation of crushed brick, referred to as surkhi in South Asian practice, seems to have been a deliberate alteration aimed at improving workability and introducing mild pozzolanic reactivity, a trait similarly noted in recent studies of heritage lime mortars throughout South Asia (Bakshi, 2020; "<IJCS-22-33_Shukla.pdf>,").

The non-existence of the hydraulic phases like belite or aluminates confirms that the mechanical strength of the binders is almost solely based on carbonation, and makes it very permeable and subject to environmental changes. This finding positions Poonch House among other similar lime mortars from the colonial period that Ottawa has, which comprise good vapour permeability with poor resistance to salt crystallisation and acid attack via polluted urban atmospheres.

23 Deterioration Mechanisms in Climatic and Environmental Context

The results collectively suggest that the degradation of Poonch House mortar is caused by the synergistic chemical and physical processes, which are dominated by moisture ingress, salt contamination and pollution-induced sulfation. The transformation of calcitic lime to gypsum and other sulfate phases is being accelerated by the subtropical climate of Lahore with high humidity, monsoonal precipitation and high atmospheric SO_2, NO_X and particulate matter loadings. Similar mechanisms of environmental interactions have been reported in the limestone facades (Moropoulou et al., 1995; Yan & Wang).

In addition, halite formation and the determined moisture contents over 8% show the existence of active salt cycles. These cycles are caused by capillary transfer from the ground layer and by diffusion of condensation inside the wall layer metabolism. Each time of wetting and drying induces crystallisation pressures big enough to break the relatively weak cohesive bonds of carbonated lime. Also similar to observations on monuments in Lahore from the Mughal era, NaCl and $CaSO_4$ have been found to cause microcracks and detachment at structures (Gulzar & Burg, 2018; Saima Gulzar, Muhammad N. Chaudhry, et al., 2014).

Therefore, poonch house degradation is not only a case of concrete material degradation but a coupled environmental system with stress, induced from climatic environmental factors proximal or pollutant loading, interacting with underlying material weak links to induce progressive cohesion loss.

24 Microstructural and Mechanical Correlation

The combination of the data from the SEM, EDX and UPV is a rare opportunity to correlate micro-level chemistry and the macro-level mechanical response. The slowing down of ultrasonic velocities to a speed of 0.43 km s-1 corresponds directly to areas of high moisture as well as to visible efflorescence. Similar relationships between porosity increase and decrease of acoustic velocities have been shown in investigations on Portuguese lime mortars (do Rosário Veiga et al., 2010) and Turkish Ottoman masonry (Akevren, 2010; "<PhDthesis_IsinMericNursal_.pdf>,").

This strong spatial coherence indicates that the heterogeneity of the microstructure and the cracking formed under the influence of ions decreases the effective elastic modulus of the mortar. Even graphically aesthetically aggregate zones show moderate velocity drops, which means subsurface degradation - a major worry of conservation diagnostics. These results confirm the usefulness of combining non-destructive testing (UPV) and microanalytical characterisation (SEM-EDX) in order to obtain a reliable understanding of the mortars on multiple scales, where destructive sampling has to be kept to a minimum.

25 Comparative Evaluation and Conservation Lessons

In an international context, the deterioration model at Poonch House is similar to that reported for other scientific heritage structures of tropical and semi-arid climates with non-hydraulic lime as the mortar bound to elevated levels of relative humidity and air pollution. For example, gypsum crust formation and salt efflorescence have been reported for colonial facades (Arencibia-Iglesias et al., 2020; Tavares et al., 2022), These similarities assure us that this underlying mechanism-pollutant-induced sulfation with salt crystallisation is a regionally recurrent phenomenon that needs to be mitigated on a climate-specific basis.

Viewed from the conservation perspective, from the above results, one can obtain two impeccable rules:

a. Material Compatibility: Restoration mortars need to match the end properties of porosity and vapour permeability of the original lime system, as well as be resistant to sulphate attack. The current practice, as seen in some previous repair works on Poonch House, of using cement-based, or too hydraulic, mortars should, thus, be abandoned, as they introduce stiffness imbalance and cause a moisture trap, increasing the effects of salt crystallisation.
b. Moisture and Salt Management: In long-term preservation, moisture management is far more important in terms of long-term preservation than surface coatings. Other protection measures using improved roof drainage, sacrificial lime washes and local desalination poultice are more sustainable and reversible and comply with ICOMOS' principles of minimal intervention (Icomos, 1964).

26 Broader Implications for Heritage Science

The interdisciplinary approach used (Figure 11), incorporating microstructural, mineralogical, hygroscopic and mechanical analyses- has the advantage of providing a replicable analytical framework for diagnosing colonial period masonry throughout South Asia. By corrosion mechanisms, lime mortars: establishing Correlations between the environmental exposure, salt chemistry and mechanical performances. This study promotes a better understanding of the processing of climate-induced decay mechanisms within lime mortars in chemical aggressions associated with urban pollution regimes. Moreover, the results prove that the combination of high-resolution micro-analytical tools with the use of non-destructive diagnostics can detect the early stage of the deterioration before it manifests visually. Such integrated approaches have a tangible role to play in evidence-based conservation planning and feeding recommendations for the development of region-specific conservation criteria set where climatic stressors differ significantly from European reference.

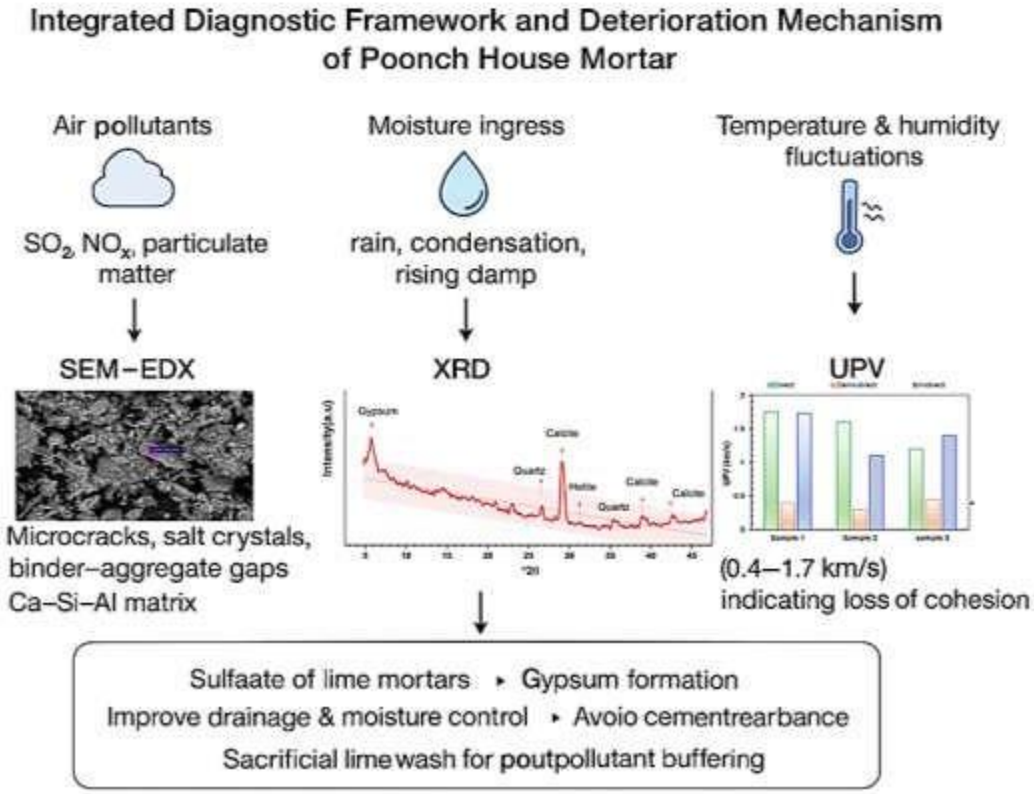

Figure 11. Integrated Diagnostic Framework and Deteriorated Mechanism of the building.

27 Conclusions

This paper has carried out an extensive research work on the structural properties, material composition and deterioration processes of the old wall mortar of Poonch House, Lahore, South Asia, which is one of the instances of colonial architectural heritage in this part of the world. By combining destructive and non-destructive methods such as Ultrasonic Pulse Velocity (UPV), scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), X-ray Diffraction (XRD) and gravimetric moisture determination, the chemical-microstructural-mechanical performance of the mortar, indicating zones of critical manifestation and active degradation, is presented.

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray analyses confirmed that the main constituent of the binder is air lime with siliceous and aluminous aggregates like sand and crushed brick. The microstructure is heterogeneous and porous, having well-defined grain boundaries and extensive microcracking, a characteristic indicative of weathering, moisture migration and long-term material fatigue. The presence of sodium, chlorine in the absorption edx spectra of the fragments, together with an average moisture content of 8.77% points to salt crystallisation and capillary transport processes in mortar, the most important factors in its accelerated destruction in polluted humid conditions. Upv allowed bringing an important quantitative dimension to the diagnostic grid. Fast pulse velocities (>1.7 km/s) are measured in protected interior surfaces, showing dense and well-carbonated lime, and low velocities (<0.6 km/s) in arch segments and exposed fronts that show attitudes that are caused by microcracking, voids and loss of cohesion. This spatial heterogeneity is the product of environmental tension and the legacy of mismatch of previous interventions, especially cement-based interventions that cause a decreased vapour exchange and increased salt concentration.

Comparable investigations with similar international case studies (the Amfissa Cathedral - Greece and the Antiochia and Cragum Temple - Turkey) show that the deterioration processes are the same in all historic lime mortars, like sulfation and salt crystallisation. However, Poonch House samples show regional differences in their utilisation: a lower salt loading, lack of fibre reinforcements, as well as a finer microstructure as an expression of climatic and material differences in the South Asian context. The use of UPV testing (rarely used in heritage mortar diagnostics) was found to be most effective in establishing microstructural weakness in relation to in situ mechanical response and to provide an easy but accurate way of gauging structural performance.

Beyond the scientific contribution of the research to the characterisation of the masonry from the colonial era, the research has direct relevance to conservation. It creates a material baseline that is needed to design lime-based repair mortars that are compatible with concrete, and it serves as a foundation to implement moisture management strategies. The results support the evidence for preventive conservation, especially considering the compound effects of air pollution, moisture ingress and material incompatibility due to previous restorations. By recording the underlying strengths and weaknesses of a deteriorated mortar, the investigation they have presented will add to scientific knowledge in sustainable heritage conservation, extending the British architectural and cultural residue that Poonch House represents in Lahore.

28 Future Directions and Limitations

While this study provides an in-depth understanding of the wall mortar, future work should include the holistic view of materials, including all components of construction, such as plasters, stone masonry, wood joinery, and metallic fittings, since they interact mechanically and chemically with the mortar. In addition, environmental monitoring, including temperature, humidity, pollutant concentrations, and rainfall, would be of significant value for modelling ongoing processes of deterioration and the validation of the effectiveness of conservation interventions over time.

The main shortcoming of this research is that only the mortar element has been analysed so far, and this, despite its centrality, does not reflect the multiplicity of relationships between the heterogeneous materials of the building. Lack of resource availability, heritage protection and accessibility constraints also restricted the final area and performance of more advanced analyses (e.g. mercury porosimetry, thermal analysis), etc. Future interdisciplinary multi-material diagnostic and environmental monitoring research is needed in order to create a predictive conservation management framework for the Poonch House building, and similar colonial period OPC buildings.

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