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CHARACTERIZATION OF SHAHDARA TOMB'S WALL PLASTERS FROM LAHORE, PAKISTAN

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Abstract

Optical microscopy, scanning electron microscopy equipped with energy dispersive spectrometer, petrography and X-ray diffraction analyses were employed to characterize the historic wall plasters from 17th century Shahdara's tomb, in Lahore (Pakistan). Three types of plaster layers corresponded to different functions and locations. The study focused on the nature, composition, texture and microstructural features of binder (lime) and aggregate (Kankar-carbonate fragments, brick pieces and slag) fractions to understand their technical and historical production. Results indicated that pozzolanic brick and slag fragments developed strong adhesion bonds with the binder, which enhanced the durability of the investigated plasters. These results would help in making materials with similar technical and compositional characteristics to set up a scientific plan for conservation and restoration purposes.

Keywords: *Mughal; Wall; Plaster; Shahdara Tomb; SEM-EDS; Lahore*

Introduction

Shahdara (King's Gateway) is located on the right bank of the Ravi River, opposite to the city of Lahore. It is approached from the north through the famous Grand Trunk Road and acts as a main entry point into Lahore, on the historic trade route linking Central Asia to the Indian subcontinent. Shahdara became the focus of architectural and political activity by the Mughals soon after the conquest of India by Babar in 1526 A.D. [1, 2]. Shahdara evolved as a halting place for the north-bound Mughal camps after crossing the river Ravi and hunting grounds of Sheikhupura during the early Mughal period. The Shahdara Complex is the largest group of surviving monuments with the transformation history of the pleasure gardens into the funeral complex [2, 3]. It has a long history, which has witnessed the majestic drama of the rise and fall of the Mughal, the Sikhs and the colonial rulers. The complex hosts four major monumental buildings and many ancillary structures beautifully landscaped with natural features. This heritage site is the collection of richly elaborated historic structures and masterpiece of aesthetically appealing planning of hard and soft landscape that evolved into the funeral landscape. The complex comprises three main monumental tomb structures placed in the centre of the independent and landscaped compounds along with the monumental Serai buildings. The tomb of Jahangir and Asif Khan are linked through the main entrance courtyard of Akbari Serai whereas the third tomb of Queen Nur Jahan aside is isolated due to the crossing railway track (Fig. 1).

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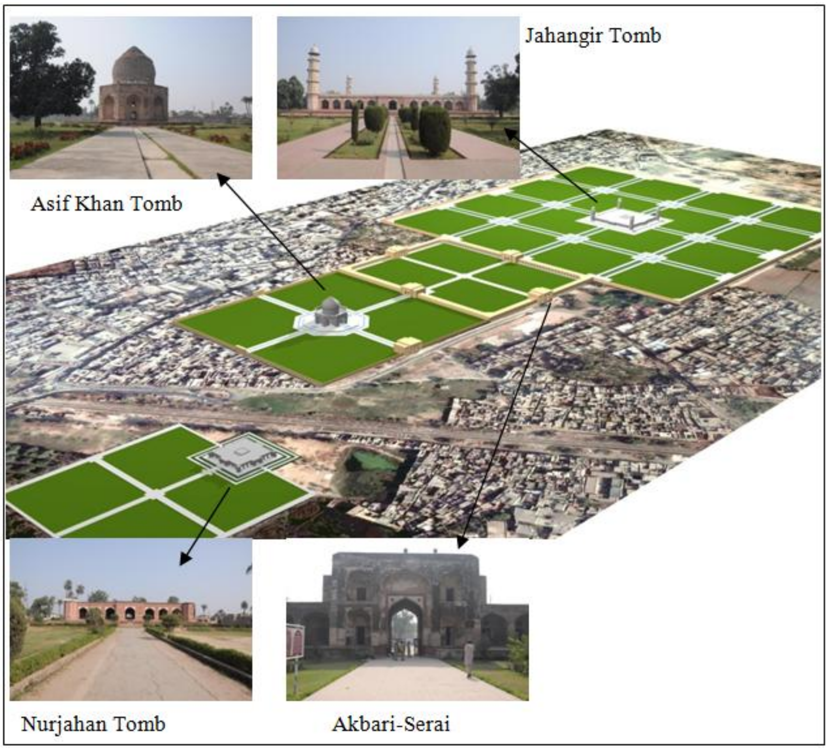

Fig. 1. 3-Dimensional reconstruction model of Shahdara Complex from Google Earth (Location: 31º North Latitude and 74º East Longitude): a - Asif Khan Tomb, b - Jahangir Tomb, c - Nurjahan Tomb and d - Akbari-Serai

The heritage site of Shahdara is in danger of decay with natural ageing and exposition to anthropogenic threats which in turns accelerated impairment [4]. The present study is based on the ICOMOS charters for conservation and restoration which are aimed at preservation and revealing the aesthetic as well as historic value of the monument while respecting its original materials and historic fabric.

Research Aims

The restoration of historic buildings began with the knowledge of materials, techniques and manufacturing processes used in their original construction. Published data concern different architectural periods of the world while the Mughal period (1526–1857), in Pakistan, was being almost ignored. The prevalent use of cement-based repair materials was found to be inducing damages to the historic masonry. The main objective of this research was to investigate and explore the historic plastering technique; the original types of binder, aggregate in addition to the mixing ratios used for the Mughal period plasters were specified with various analytical methods to generate quantified compositions of appropriate materials for future restoration.

Analytical Methods

Sampling was done according to the principle of minimum damage to the historic fabric, with a chisel and a small hammer instead of core drilling [5]. Sampling procedures were conducted with great care under the supervision of the archaeological staff and samples were taken to fulfil the analytical needs. Sample sections were photographed besides the descriptive visual examination to determine the historic plastering technique and various combinations of wall plaster layers (Fig. 2). Ten representative samples were collected from various plaster layers to obtain a complete set of information (Table 1).

Fig. 2. Close-up views of Shahdara's wall plaster layers and types

All samples were first analysed macroscopically and binder/aggregate ratios were determined by dissolution through hydrochloric acid attack, following conventional methods [6, 7].

Optical microscopy was performed on thin sections, prepared following the procedure described by Elsen [8, 9] and examined with transmitted and polarized light to determine the mineralogical composition, textures and grain sizes [10].

The Scanning Electron Microscope (SEM), JEOL JSM 6390 LA coupled with EDS (Oxford-1 NCA) spectrometer operating at an accelerating voltage of 15kV was used on polished surfaces of vacuum impregnated samples in epoxy resins to study the texture and to detect chemical compositions at binder and aggregate interfaces.

X-Ray diffraction (XRD) was performed on bulk samples for complete determination of mineral phases. The diffraction patterns were collected using a Bruker, AXS D8 Advance powder diffractometer (CuKα radiation) equipped with the Lynxeye super speed detector system.

Table 1. Description of the studied samples and their photographed locations

Description	Photograph	Sample #	Plaster Layer Type	Binder	Aggregates		Binder Aggregate Ratio (with HCL acid reaction)
					Coarse	Fine	
Sample-1 Wall plaster consists of three layers coarser, fine and finishing top layer		CP-1-9	Brownish-coarser	Lime, Clay	Brick, Kankar, Slag	Sand	1:1.5-2
		FP-1-21	Dirty White-fine	Lime		Brick, KankarSand, Slag	1:1/2
		TP-1-218	Whitish-finishing	Lime		Sand, Surkhi	1:1/8
Sample-2 Wall plaster consists of three layers of plaster (coarser, fine, top) and an additional layer of mortar applied first before plastering		MP-2-25B*	Dark Brown-mortar	Lime	Brick, Kankar, Slag	Sand	1:3
		CP-2-25	Brownish-coarser	Lime, Clay	Brick, Kankar, Slag	Sand	1: 1.5-2
		FP-2-109	Dirty White-fine	Lime		Brick, Sand, Surkhi	1:1/2
		TP-2-417	Whitish-finishing	Lime		Sand	1:1/8
Sample-3 Wall plaster consists of five layers comprising of coarser, 2 layers of fine, top finishing plaster with an additional decorative layer		CP-3-92	Brownish-coarser	Lime	Brick, Kankar	Sand, Slag, Clay	1: 1.5-2
		FP-3-113	Dirty White-fine	Lime		Brick, Sand, Surkhi	1:1/2
		FP-3-113B	Dirty White-fine	Lime		Brick, Sand, Surkhi	1:1/2
		TP-3-423	Whitish-finishing	Lime		Sand	1:1/8
		DP-3-423B*	Creamy White Glazed Surface-decorative	Lime	Pure Lime is mixed only with curd in a ratio of 1:2 (Fazal, 1989)		

* Samples not analysed for this particular study on plastering technique

Results

Visual and Macroscopic Description of Studied Plaster Samples

Multi-layered plastering technique was employed in the monuments of Shahdara during the Mughal period (1527-1645). The plaster layers were easily distinguishable by their different colours as well as through exposed weathered layers (Fig. 2).Three different typologies/ combinations of plaster layers were identified during the site studies. The first type (Fig. 2a, b and e) comprised of a coarse layer, coated by a fine layer and a finishing top layer. The second type (Fig. 2c and f) was distinguished due to an additional layer of mortar used as a base coat on the walls with further application of a coarse, fine and finishing plaster layers. The third type (Fig. 2g) was found to have five layers in which the base, coarse layer was followed by two coats of fine plasters with the finished coat of top plaster layer that all served as base for decorative detailing including murals, glazed plasters and mouldings etc.

The macroscopic description of the three main layers was found to be as follows (Table 1):

- Coarse plaster light brownish coloured, applied in thick layers (25-35mm) of coarse brick, Kankar-calcareous nodules and slag fragments and sand as a fine aggregate in a binder mixture of lime and clay.
- Fine plaster dirty white coloured in layers of medium thickness (10-25mm) mainly composed of small sized finely crushed fragments of brick and slag and very fine sand in small proportions with lime binder. Fibrous material was also observed in this layer.
- Finishing top plaster whitish coloured in thin (5 mm) and hard calcitic layer with only small fractions of aggregate if any.

These three typologies were used for different locations depending upon function. The first type was mainly used to plaster the architectural elements comprised of brick masonry core structure such as walls, columns, pillars, and arches. The second plaster type was used for exterior locations directly exposed to the atmospheric parameters where the base coat of mortar act as an insulating layer between brick core and plastering layers, in addition to increasing thickness of overall plaster layer (technique used to slow down the inward moisture travelling). The third type was mainly employed for decorative purposes on external surfaces.

Petrography and Microscopy

In Optical microscopy, all the investigated samples of coarse plaster showed mainly calcite lime binder prepared from burning of Kankar-calcareous nodules with a small proportion of clay (ca. 20%), aggregate and up to 1% of fibrous material. The binder fraction (70-75%) predominantly grouped into clustered structure with ca. 5% of mostly large irregular pores. The heterogeneous matrix is made of with 25-30% coarse fragments (0.5-1.0mm big) mainly of brick (8-10%), Kankar (10-12%) and brick kiln slag (1-3%) in addition to 4-5% poorly sorted quartz from silt size up to 1mm coarse sand (Fig. 3a).The aggregates were found poorly rounded or angular grains. Microscopic investigation further revealed binder/ aggregates strong adhesion through reaction rims.

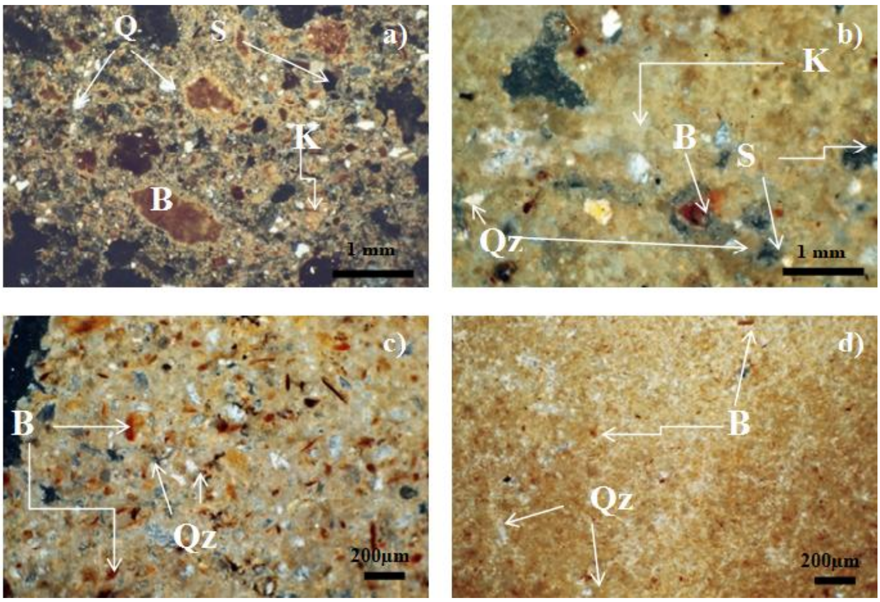

Fig. 3. Micrographs of plaster layers: a - coarser plaster b - fine plaster where 2 coats were applied c - fine plaster and d - top plaster showing lime binder-carbonate (L), quartz (Qz), Brick Piece (B), Slag(S) and Kankar (K) embedded in the Lime binder in investigated samples.

The investigated samples of fine plaster exhibited <0.25mm fragments (10-15%; Fig. 3b and c) of chopped brick pieces, Kankar and slag mainly elongated and angular pieces embedded in lime binder (85-90%) with cca. 1-2% pore spaces. Subordinate angular to poorly rounded siliceous sand grains were found similar to the quartz in coarse plaster (Fig. 3b). The matrix was microcrystalline and fine grained. Reddish brown specks and stains of iron oxide were observed at high magnification.

The finishing plaster is cca. 95% micritic calcite with negligible amounts of small pores (< 0.5%; Fig. 3d). The < 5% fine aggregates included quartz grains silt to very fine sand (0.005 to 0.05mm) sized and powdered brick producing reddish iron oxide spots visible at high magnification.

X-Ray Powder Diffraction

The X-ray powder diffraction patterns (Fig. 4a) showed that the coarse plaster was mainly composed of calcite-carbonate phase, silica-quartz and clay phase (illite) as identified by microscopy. The highest intensity peaks were found for calcite and quartz (Table 2). The clay phase-illite was determined with intermediate peaks while the low intensity peaks were attributed to minor phases: albite, haematite and K-feldspar/microcline in few samples.

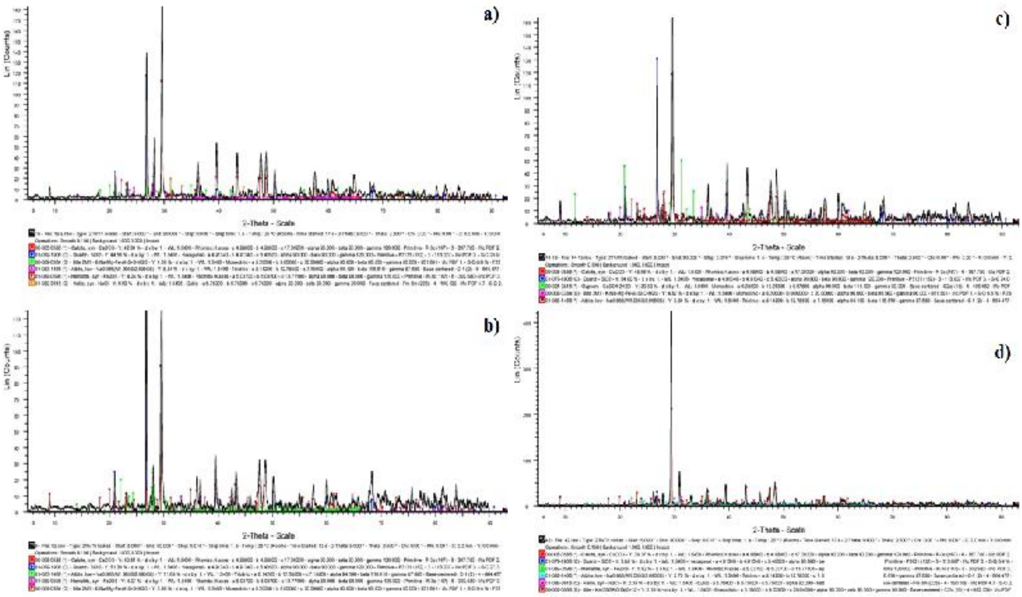

Fig. 4. Typical XRD patterns for samples: a - coarse plaster layer, b - fine plaster layer, c - fine plaster layer and d - top finishing plaster layer

X-ray powder diffraction patterns (Fig. 4b and c) of fine plaster showed highest intensity peaks for calcite. Medium intensity peaks for silica-quartz and low peaks for clay-illite phase, albite, haematite and K-feldspar/microcline. Additional mineral phases were found to be the traces of gypsum and halite (low peaks in Fig. 4b and c; Table 2), which were deterioration products. They were also visually observed as white and black crust on exposed surfaces.

The X-ray powder diffraction patterns of finishing plaster (Table 2) showed calcite as main crystalline phase with low peaks for silica-quartz, clay-illite, albite, haematite, gypsum and halite (Fig. 4d).

Table 2. Results of XRD analysis of investigated plaster samples

Sample	cal	gyp	qtz	ill	alb	hem	hal
CP-1-9	+++	-	+++	++	+	+	-
CP-2-25	+++	-	+++	++	+	+	+/-
CP-3-92	+++	-	+++	+	+	+	-
FP-1-21	++++	+/-	++	+	+/-	+	+/-
FP-2-109	+++	+	++	+	+/-	+	+/-
FP-3-113	+++	-	++	+	+/-	+	-
FP-3-113B	+++	-	++	+	+/-	+	-
TP-1-218	++++	+	+	+	+/-	+	-
TP-2-417	++++	+/-	+	+	+/-	+	+/-
TP-3-423	++++	-	+	+	+/-	+	-

Cal-calcite, gyp-gypsum, qtz-quartz, ill-illite/clay, alb-albite, hem-hematite, hal-halite
++++ dominant, +++ abundant, ++ present, +small amounts, +/- traces, - not detected

Scanning Electron Microscopy and EDS

Microstructural features of the plaster samples were studied by scanning electron microscopy coupled with EDS. The three plaster layers (Fig. 5, 6 and 7) revealed high percentages of calcite with varying proportions of quartz in coarser, fine and finishing plaster layers. The high proportion of calcite reveals that pure lime was used with the aggregates rich in silica-quartz. In the SEM images, it was also observed that the aggregates and the binder were bounded by reaction rims (Fig. 5, 6 and 7). The chemical composition at the binder-aggregate interface conducted with EDS is characterized by high proportions of calcium, silicon and aluminium. The amounts of calcium in binder and of silica in aggregates were larger than at interfaces due to the formation of hydraulic products calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) at interface.

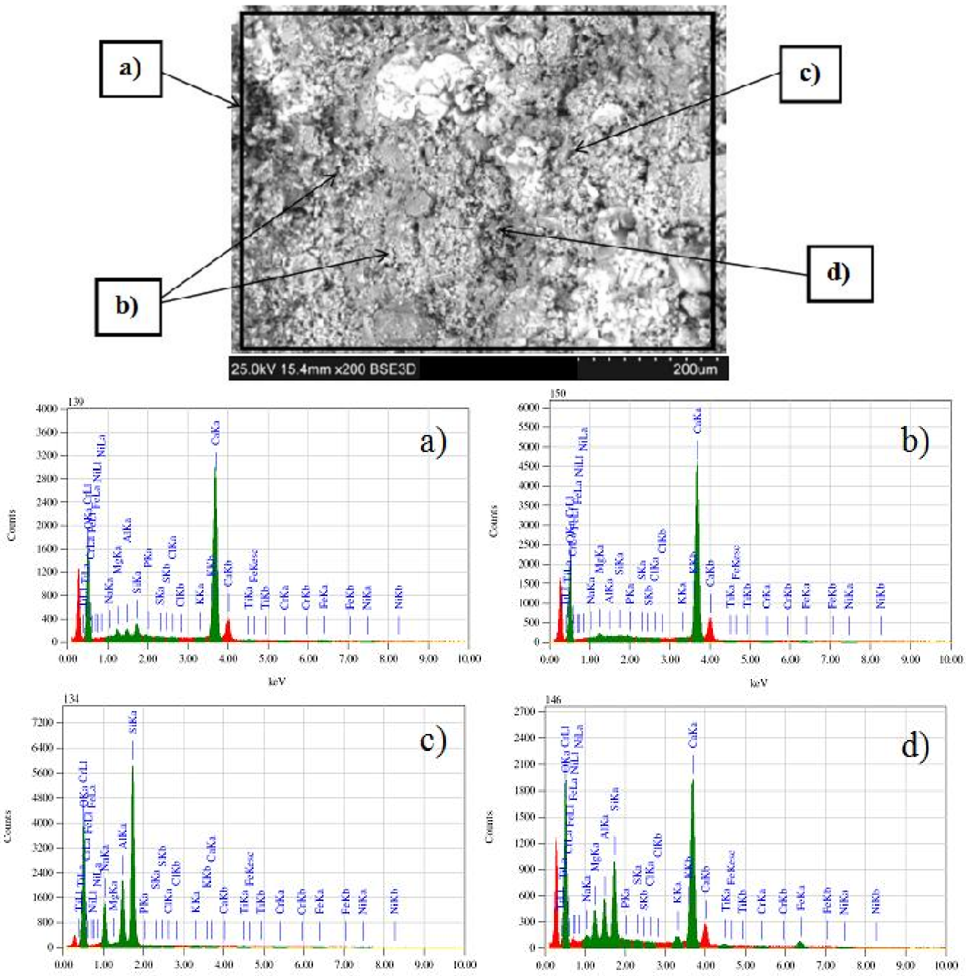

Fig. 5. BSE image of top plaster layer and EDS spectra taken from points corresponding to: (a) area analysis, (b) binder, (c) aggregate and (d) reaction rim

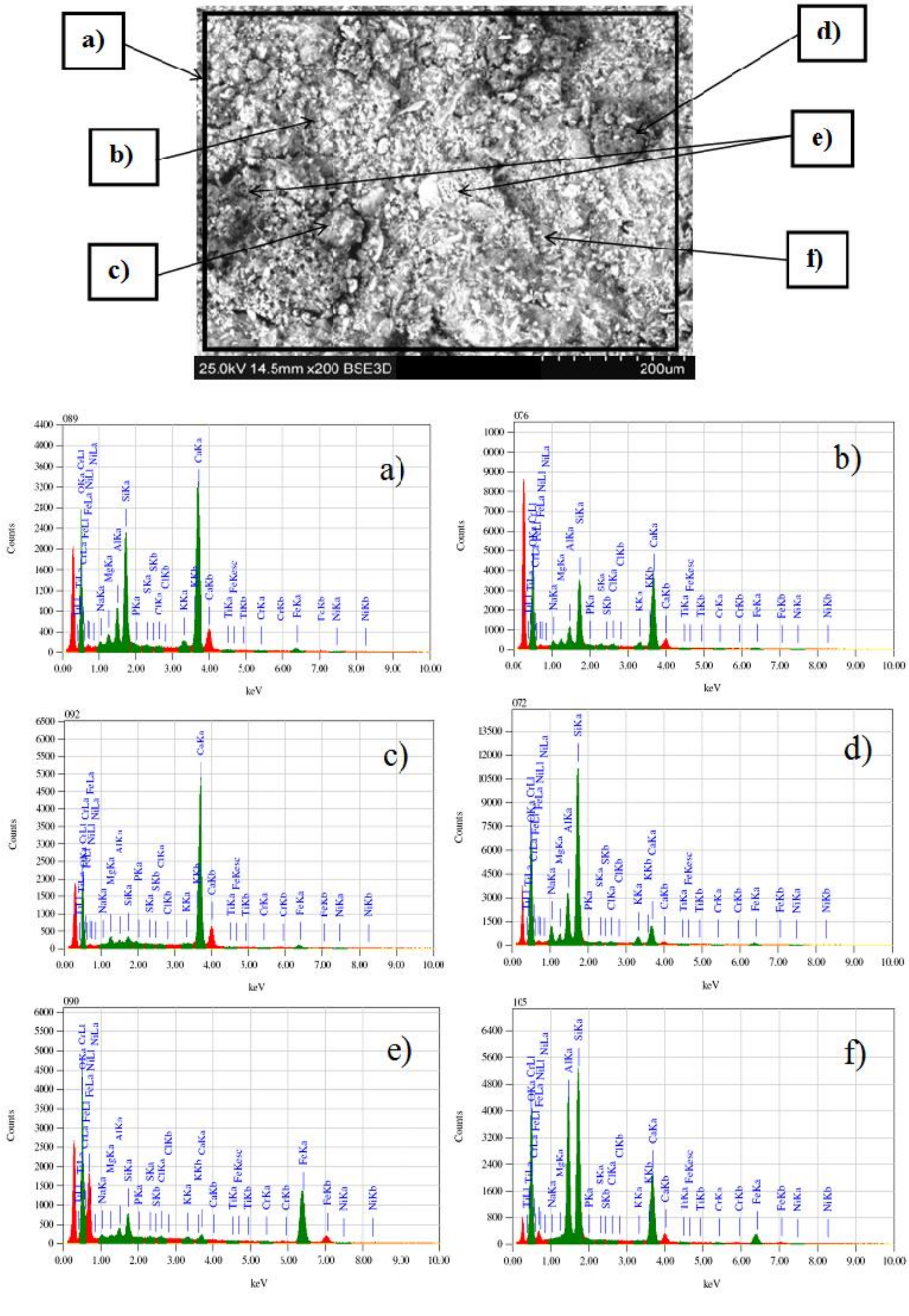

Fig. 6. BSE image of coarser plaster layer and EDS spectra taken from points corresponding to: a - area analysis, b - binder; aggregates: c - kankar, d - brick pieces, e - slag particles and f - reaction rim

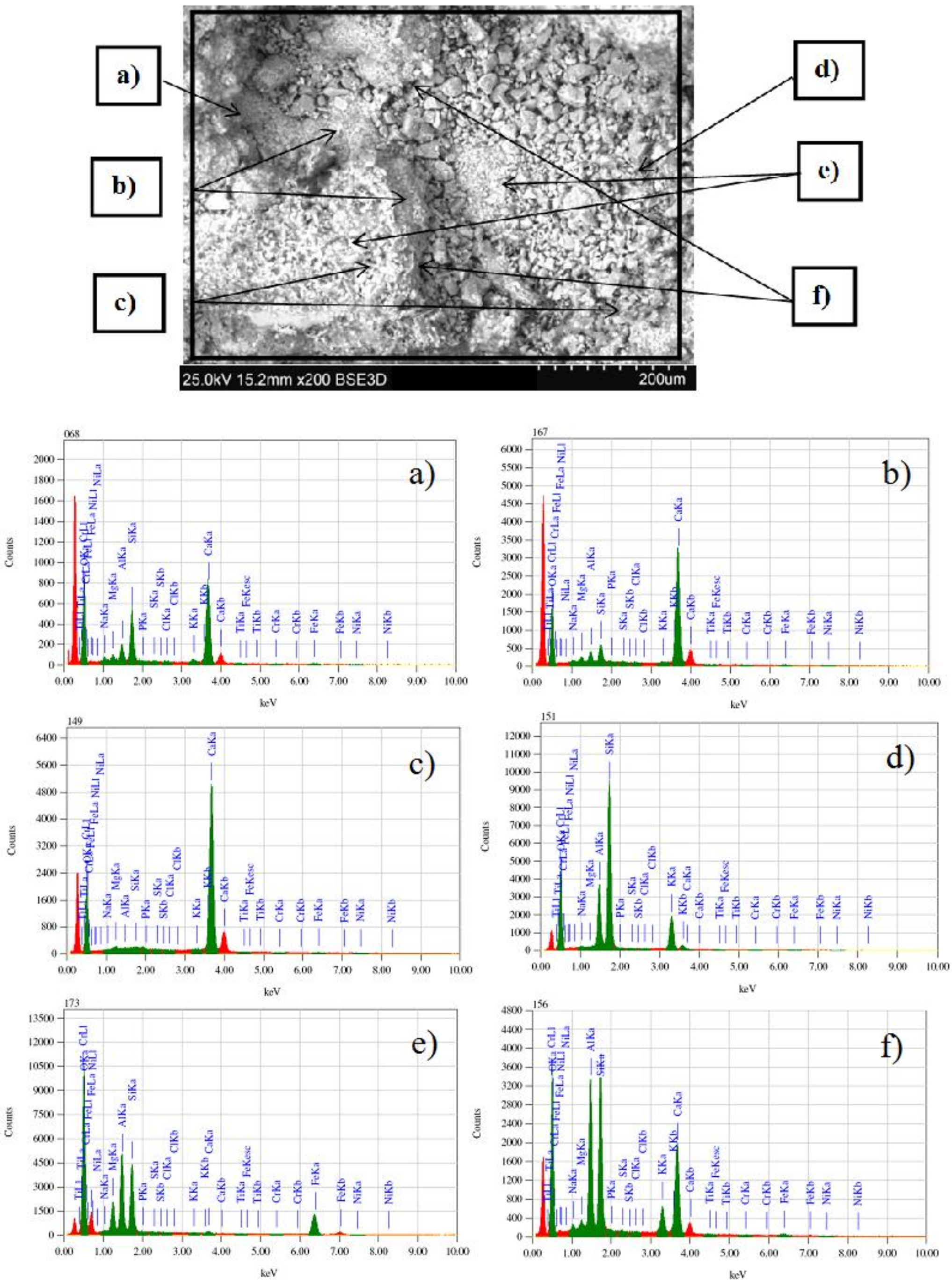

Fig. 7. BSE image of fine plaster layer and EDS spectra taken from points corresponding to: a - area analysis, b - binder; aggregates: c - kankar, d - brick particles, e - slag particle and f - reaction rim

Discussion

The heritage sites had been the historical documents of the period in which they were constructed accumulating the essence of that period. Analytical studies of historic materials unfolded the information about the employed materials and technology that were found to be necessary for the conservation and restoration with compatible materials. The results of studied historic plasters that survived through more than 400 years on the walls of Shahdara tombs showed the careful choice of each component; binder, aggregates and organic additives as discussed in detail below:

Characteristics of Lime Binder: All investigated samples were rich in lime binder ca. 70% in coarse plaster, 90% in fine plaster and ca. 95% in coating plaster. These values were found to be similar to those in plasters of Hagia Sophia, in Istanbul [11, 12]. This high lime content could be attributed to the presence of Kankar-lime nodules added as aggregate in the preparation of these plasters historically. However, the binder lime content was found to be relatively high irrespective of this aggregate content in some other studies [13, 14]. The collective analyses of optical microscopy, SEM-EDS and XRD revealed that binder in all plaster layers was mainly composed of micritic calcite crystals together with very fine size siliceous grains. This also implied strongly advanced carbonation of $Ca(OH)_2$,which is typical of historic, lime-based plasters, in which portlandite has almost totally converted to micritic calcite [15, 16]. The formation of Kankar lime in the Mughal period was found to be related to its abundance in the area. The Kankar (calcareous nodules) were subjected to calcification process by burning around 900°C to give off CO_2 (Eq. 1) and afterwards slaked with water (Eq. 2). The slaked lime was transformed to calcium carbonate by the help of atmospheric CO_2 and water to be used as binder in plasters [17-19].

$$CaCO_3(s) \longrightarrow CaO(s) + CO_2\,(g) \qquad \text{(Calcination process)}$$
$$CaO(s) + H_2O\,(l) \longrightarrow Ca\,(OH)_2(s) + \text{heat} \qquad \text{(Slaking process)}$$
$$Ca\,(OH)_2 + CO_2\,(g) \longrightarrow CaCO_3(s) + H_2O + \text{heat} \qquad \text{(Carbonation process)}$$

The pozzolanic products in the matrix (Fig. 4, 5 and 6) suggested the inclusion of pozzolanic aggregates in addition to other type of aggregates to improve the performance of these plasters [20, 21].

Characteristics of aggregates

The percentage of aggregates was found to be in the range of 5-25% in all investigated plaster layers. The petrographic analyses in combination with SEM-EDS observations identified carbonate aggregates (Fig. 3a, b and Fig. 5c, 6c), brick pieces (Fig. 3a, b, c and Fig. 5d, 6d, and 7c) and slag pieces (Fig. 3 a, b and Fig. 5e and 6e) as pozzolanic aggregates in addition to fine aggregate sand [8, 9, 21]. The Kankar-carbonate aggregate was mainly composed of calcite with negligible amounts of other minerals and was found in abundance in the vicinity of the Shahdara site, which made it a most suitable component. The brick pieces were porous and their chemical composition (Fig. 5d, 6d, and 7c) is similar to that of Mughal bricks prepared from calcium poor clays fired at low temperatures [22, 23]. The use of brick pieces further supported the higher content of silica and alumina at the brick and lime interface (Fig. 5f, 6f and 7d). The added slag pieces were also found to be porous and iron-rich (Fig. 5e and 6e). The slag was not commonly used in historic plasters but it was studied in some Ottoman monuments as a pozzolanic aggregate [24, 25]. Similarly, in Shahdara wall plasters, presence of slag further confirmed its use as pozzolanic aggregate. The reaction rims around the brick and slag particles (Fig. 3, 5, 6 and 7) developed strong adhesion between lime binder and aggregate. The high pozzolanicity of the aggregates resulted from the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). The high concentrations of these elements at binder-aggregate interfaces (Fig. 5f, 6f and 7d) in addition to strong adhesion had imparted plasters the mechanical strength that made them survived through centuries [26-30].

Characteristics of Additives

The fibrous organic material was jute added for reinforcement purposes and to increase the bonding strength of the plaster matrix. Jute fibres also supported crack free hardening by absorbing the stresses developed during the wetting and drying periods as studied by Chandra [4, 12].

Plastering Technique

The multi-layer plastering technique used for Shahdara's tomb during the Mughal period (1527-1645) involved first application of coarse plaster layer (25-35mm) on brick masonry that ensure strong adhesion between materials for easy air and water circulation through pores during settling period. Fine plaster layer (10-25mm) was then applied to make a stronger less permeable layer. The top finishing plaster layer (5mm) makes the whole plaster impermeable by interlocking all the pores [31-34].

Conclusions

The study of wall plasters from Shahdara's tomb in Lahore, Pakistan revealed three types of plastering during the Mughal period. The first, most commonly used type comprised of three outward-finishing layers: coarse, fine and finishing. The second type was differed by the application of mortar as base coat beneath the coarse, fine and finishing layers. The third was distinguished by the combination of five layers starting from coarse plaster layer with two layers of fine plaster whereas the finishing is covered by another decorative layer.

The pure lime binder used in these plasters was derived from locally abundantly available calcareous nodules (Kankar), slaked with water after calcification. The aggregates were mainly comprised of siliceous brick pieces, slag and sand in addition to fragmented carbonate (Kankar nodules). The addition of brick and slag (bearing the pozzolanic characteristics) was to achieve advanced carbonation making plasters more durable as permeability decreases with advance carbonation. SEM-EDS analyses also showed the good adherence of binder and aggregates with C-S-H and C-A-H bonding that resulted into well carbonation of the matrix.

The structures of investigated plasters were based on their function and application. The coarse plaster layer was applied as a base coat on the brick masonry. The fine plaster layer with fibrous jute as additive proved to be smoother and less porous than the coarse layer. The finishing layer was applied as a protective covering and sealing all the layers to make one monolithic mass and weather resistant surface.

The studies also highlighted traces of gypsum and halite as white and black crusts attributed to atmospheric pollution.

The investigated historic plaster components, their composition and application technique will enlighten the conservation and restoration works for the strengthening of the historic structures of Shahdara tombs in Pakistan. New plasters could be made based on this analytical data to avoid further use of cement plaster, which already damaged much part of these cultural assets.

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