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ANALYTICAL STUDY OF THE LIME MORTARS USED IN MUGHAL'S AND LATER PERIODS IN THE HISTORICAL SITES OF PUNJAB PAKISTAN (A CASE STUDY OF AKBARI MAHAL, AKBARI GATE AND ROYAL KITCHEN LAHORE FORT)

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Abstract

Mughal's (1566 A.D-1674 A.D), Sikh's (1799 A.D – 1839 A.D), British (1846 A.D – 1927 A.D) and Post-Independence periods (1947 to date) are the most important one in the Archaeology of Pakistan in which lime mortar is extensively used either to construct the monuments all over the Punjab and also within the Lahore Fort complex (Mughal Period) and then to preserve/restore (Sikh's, British and Post-Independence periods) several times. The compatibility of the mortar is important to understand before any repair/renovation work. Three monuments named as Akbari Gate, Akbari Mahal and Royal Kitchen within the complex of Royal Fort Lahore is selected. All these selected monuments have lime mortar samples of each period, which is the Mughal, Sikh's, British and Post-Independence one. Care is taken while extraction of lime mortar under the supervisions of historians and conservators with the help of sludge hammer and chisel. Well established techniques "Wet Chemical Analysis" and "XRD" (X-ray powder diffraction) have been used to evaluate % of $CaCO_3$ and other ingredients present in lime mortar specimens. Through wet chemical analysis we found the Lime (CaO), Mixed Oxides (R_2O_3) and Silica (SiO_2). Whereas through XRD, we calculated the % of $CaCO_3$, % of aggregates (Silica etc.) and their minerals as well. Both types of experiments show the presence of lime as binding materials along with other ingredients in certain proportions. Finally, tables of comparison and graphs are developed with respect to these variations, to check the % of deviations with respect to each period.

1. Introduction

The architectural heritage of Pakistan is a physical chronicle of the region's complex socio-political history, characterized by the successive influences of the Mughal, Sikh, and British empires, leading into the modern Post-Independence era. Among the most significant archaeological sites in South Asia, the Lahore Fort (Shahi Qila) stands as a testament to these transitions, particularly the Mughal period (1566 A.D. – 1674 A.D.), which established the site's primary monumental scale (Khan, 2004). However, the subsequent Sikh (1799 A.D. – 1839 A.D.) and British (1846 A.D. – 1927 A.D.) administrations, followed by contemporary conservation efforts (1947 to date), have introduced various layers of structural interventions and restorations.

Lime mortar is a crucial material whenever the life span and architectural soundness of these monuments are concerned. Traditionally, binders based on lime were preferred because of their ability to breathe, be flexible, and autogenous healing capability that enabled masonry to resist stresses of the environmental conditions over centuries (Cowper, 2000). As far as the Punjab region is concerned, the lime mortar was not only the main material used in the original construction in the Mughal times but also in the repair and preservation of the same in the Sikh and British eras. Although it was very common historically, the formulations of these mortars have changed over time as a result of alterations in the sources of raw materials, additives as well as technological advancements in the art of masonry. Reducing the historic masonry needs a thorough comprehension of the interoperability of the materials. When incompatible repair mortars are used, i.e., those having too much stiffness or having dissimilar thermal expansion coefficients, the degradation of the original substrate may occur at a faster rate (Gulzar et al., 2013). Thus, a successful renovation process involves the characterization of the chemical and mineralogical composition of the existing mortars as a precondition to any successful renovation work. Three monuments of the Lahore Fort complex the Akbari Gate, the Akbari Mahal and the Royal Kitchen offer a unique chance to research these differences because they offer specimens of mortar that represent all four great historical periods. Scientific characterization is necessary in order to obtain an accurate conception of these materials. The elemental contents of lime-based materials, namely the existence of lime (CaO), mixed oxides (R_2O_3) and silica (SiO_2) are still determined by wet chemical analysis, which is a time-honored method used. Moreover, the use of X-ray Powder Diffraction (XRD) provides the possibility to identify crystalline phases and to obtain the information about the portion of the Calcium Carbonate ($CaCO_3$) as well as the type of aggregates utilized (Elert et al., 2002).

The paper will attempt to measure the chemical deviations and mineralogical changes in lime mortar in the Mughal, Sikh, British, and the Post-Independence periods in the Lahore Fort. Through comparing the outcomes of the wet chemical analysis and XRD, the study leads to a baseline of the ratios of binding materials and aggregates applied in various periods of time. The resultant comparison tables and graphs will be a technical guide that conservators will use to make sure that future restoration activities will be historically accurate and chemically compatible with the existing fabric of the archaeological landmarks of Pakistan.

2. Materials and Methods

2.1 Identification of Lime Mortar Specimens.

The approach to determining the original Mughal specimens and the latter periods was conducted as follows considerations and steps were taken into consideration.

- One peculiarity of the masonry of Mughal is the fact that the mortar joints are as thick as the cut, dressed tile of brick.
- Agglomeration/coarser particles/aggregates such as brick ballast, Kankar lime, and jute particles can be observed easily through the mortar joints of the original work done by Mughal.
- The specimens of British period and Sikh period (lime mortar) were recognized by the expert archeologists and historians.
- The Archaeology Department determined the date card that has been engraved on the structures as the Post-Independence conservation work.

2.2 Extraction of Lime Mortar Specimens & Packing

The material was removed smoothly without breaking the building fabric with the assistance of sludge hammer and chisel. These were taken out of that section of the buildings, which already required the repair/renovation services. Without chisel and hammer the lime mortar specimens of the Sikh period and Post-Independence period was procured. Each building, i.e., Akbari Gate, Akbari Mahal, and Royal Kitchen, has 3 mortar specimens of lime, that are of each period, and they were packed individually in large zipper polythene bags. Therefore, a total of 12 specimens of the lime mortar were gathered **(Figures 1-4).**

Figure 1 &2: Inspection Team Heading Towards Monuments in the Left Figure and Inspecting Mughal's Lime Mortar in the Right Figure

Figure 3 &4: Extraction of British Period Lime Mortar Specimen in the Left Figure and Packed Specimens in the Right Figure

2.3 X-Ray Powder Diffraction of Lime Mortar Specimen

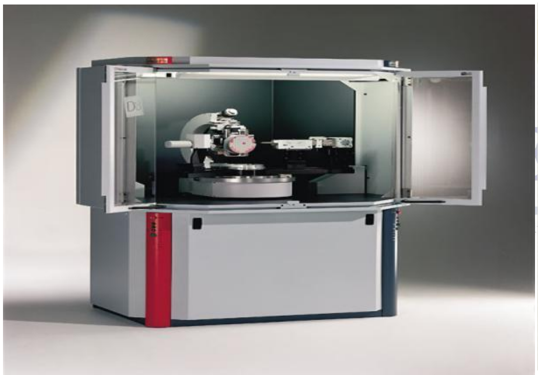
The following procedure was adopted to conduct X-Ray diffraction for testing lime mortar specimens. The machine mode was Bruker's X-Ray Diffractometer **(Figure-5).**

2.3.1 Sample Collection and Preparation

- To begin with, I got a couple of grams of the mortar, maybe a pure one.
- Then put the sample in a fine powder form. Ideally the size of the powder must be below 10 micrometers.
- Obtained a specimen holder and put powder in it (Figure 6).
- Then it was put in specimen container.
- It was then sprayed on double sticky tape.
- The creation of a flat upper surface was done carefully with care and a random distribution of lattice orientations except in the case of an oriented smear.
- In the case of unit cell determinations, a little of a standard with known peak positions can be added and utilized to correct position of peaks.

2.3.2 Data Collection Data Recording

The X-rays with their intensities are recorded as the specimen and detector rotate with their respective angles. When lattice lanes with d-spacing diffract at the value of θ contain in a mineral (calcite, quartz etc.), a peak of intensity will occur. By the diagrams it is evident that at low values of θ each peak is made up of two distinct reflections. The higher the value of θ the more it is separated. Presentations are usually of a table of results expressed as the peak positions at 2th and X-ray counts (intensity) in a table or as an x-y graph.



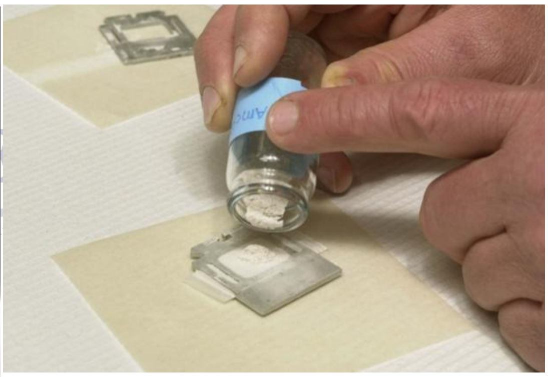


Figure 5 & 6: Bruker's X-Ray Diffractometer in the Left Figure and Pouring of Specimen in the Right Figure

2.4 Wet Chemical Analysis of Lime Mortar

The wet chemical Analysis is the process, where the mixed ratio and all the possible ingredients that can be used in the lime mortar are calculated in the percentage form. The author embraced the process as per the standard B.S 4551 Part-I.

2.4.1 Sampling (Hardened Mortar)

Sampling of the mortar was the first one. It entails the following steps.

- Regular spaced positions were used to take the specimens.
- Sampling was done in three more or less equal portions.
- The increments had a minimum of 100 grams of material.
- Lastly, it was made sure that no fine material was lost.

2.4.2 Preparation of Specimens

The preparation of the specimens included the following steps.

- To begin with, there was a guarantee that there was no contamination/constructional material like bricks, paint, whitewash, or any other potential impurity in the lime mortar samples.

- The second step was to dry the specimen in 105 ± 5C until all the moisture was removed.
- The third step involved grinding the specimen of the lime mortar with a lot of caution by hand.
- Lastly, a B.S. 410 test sieve number 36 was used on the specimen.

2.4.3 Preparation of Solution for Analysis

The following steps were involved in the preparation of the solution.

- At the initial step, 50 grams of specimen were dissolved in 500 ml of HCl solution (1:9).
- Then the solution was warmed and filtered using filter paper No. 41.
- Lastly, 1000 ml of the solution was made by addition of finely filtered water.

2.4.4 Determination of Silica

To start with, silica was determined using the ready solution. To compute the percent silica, the given steps were taken.

- 50ml solution + 10ml concentrated HCl.
- Dry and heat the dried product at 105±5C, 1 hour.
- Add 5 ml concentrated HCl + 40 ml distilled water and stir while allowing it to cool down within a few minutes.
- Wash the residue with hot water and No. 41 twice with warm HCl (1:9).
- To initiate the precipitate at 1200C to obtain constant weight. Add 2 ml water + 2 to 3 drops of the H_2SO_4 + 5 ml HF + evaporate to dry + heat 1200 C± 50C to a steady weight + cool. The following formula was used in calculating the percentage of silica.

Percentage of Silica = the weight of Precipitation x 40

2.4.5 Determination of Mixed Oxides (R_2O_3)

The filtrate of the silica was used to determine the mixed oxides. The following steps are involved to calculate the % of mixed oxides.

- Take the filtrate of silica + 5ml bromine water +heat to boiling.
- Add Ammonia Solution to just alkaline + stir for a few minutes.
- Filter the solution through No. 41 + wash with 1% Ammonium nitrate solution.
- Retain the filtrate for the determination of lime.
- Dissolve precipitate in hot HCl (1:1) + wash the filter paper with hot water and ammonia solution.
- Bring to boiling + add ammonium solution to just alkaline + filter.
- Wash the precipitate with 1% ammonium nitrate solution + ignite at 1000 C for 45 minutes + cool + weigh.
- To calculate the percentage of mixed oxide the following formula was used.

% **Mixed Oxide R_2O_3 = Weight of Precipitates x 40**

2.4.6 Determination of Lime CaO

The filtrate of the mixed oxides was used to determine the CaO. The following steps are involved to calculate the % of CaO.

- Take filtrate from Mixed Oxide + reduce the volume up to 250 ml by evaporation.
- Boil + 2-3 grams Ammonium Oxalate + 5 ml Ammonium Hydroxide Solution (1:2) till the precipitation.
- Let the precipitate settled for 30 minutes + filter through No. 41 + wash with 1% Ammonium Oxalate Solution.
- Dry the precipitate + Ignite at 1000 C for one hour + Cool in desiccator + Weigh + Reheat at 1000 C for 15 minutes + Cool + Weigh.
- To calculate the % of CaO the following formula was used.

% **Calcium Oxide (CaO) = Weight of Precipitate x 40**

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Figure 7 & 8: Wet Chemical Analysis of Lime Mortar Specimen, Heating in the Left Figure and Filtration Process in Right Figure

2.5 Crushing Strength of Lime Mortar

The procedure was exactly according to the standard ASTM C-67 or BS- 3921.

2.5.1 Preparation of Specimens

Lime mortar specimens especially for the purpose of checking crushing strength were segregated and packed in small air tight polythene bags. These specimens were opened and grinded in the laboratory manually into powder form. Care was taken so that no important ingredient of the specimen could be wasted. After grinding each specimen was packed into another similar polythene bag and marked with specific description. In the similar way all the specimens were packed and marked with descriptions after grinding.

2.5.2 Moulding, Demoulding & Curing (Air Curing)

The 2" x 2" x 2" gang cube moulds were used for moulding the mortar specimens. First of all, the moulds were washed and cleaned properly to remove all the impurities from the moulds. Then moulds were dried and their inner walls and base plate were oiled properly so that the specimen cubes can be de-moulded easily after they set. Then water was mixed in a suitable proportion with the powdered lime mortar sample and within two minutes of mixing, placed a layer of mortar about 25 mm (1") thick in all the compartments of the gang cube moulds. Tamped the mortar in each cube compartment 32 times for about 10 seconds. Filled the compartments with remaining mortar and re-tamped as for first layer. Then struck off the top surface and levelled it **(Figure-9 &10).** All the 12 specimens were de-moulded after 24 hours and cured at room temperature for 14 days through air known as carbonation process **(Figure 11&12).**

2.5.3 Test for Crushing Strength

The cube specimens were given numbers with a permanent marker on their top face from 1 to 12. Then these cube specimens were carefully placed on a wooden board and taken to the 9000 Kg gauge manual hydraulic compression machine and crushed each cube one by one and reading on the scale were noted in Kg **(Figure 13&14).**


Figure 9 & 10: Moulding Process in the Left Figure and Final Ready moulds in the Right Figure


Figure 11 & 12: De-moulding Process in the Left Figure and Air Carbonation Process in the Right Figure


Figure 13 & 14: Weighing Process in the Left Figure and Checking of Crushing Strength in the Right Figure

3. Results

3.1 Results of Wet Chemical Analysis of Lime Mortar Specimens

The results of the wet chemical analysis of lime mortar specimens are given below.

Table 01: *Wet Chemical Analysis of Lime Mortar Specimens, Akbari Gate Lahore Fort*

S.No.	Description of Specimens	Insoluble Residue (in HCl) %	Mixed Oxides (Al_2O_3,Fe_2O_3, Ti_2O_3) %	Calcium Oxide (CaO) %	Insoluble Residue (in HCl) %+ Calcium Oxide (CaO) %
1	Akbari Gate Mughal Period	47.82	32.51	15.67	63.49
2	Akbari Gate Sikh Period	63.72	26.48	7.50	71.22
3	Akbari Gate British Period	67.56	8.14	23.30	90.86
4	Akbari Gate Post-Independence Period	66.50	16.23	16.50	83.0

Table 02: *Wet Chemical Analysis of Lime Mortar Specimens, Akbari Mahal Lahore Fort*

S.No.	Description of Specimens	Insoluble Residue (in HCl) %	Mixed Oxides (Al_2O_3, Fe_2O_3, Ti_2O_3) %	Calcium Oxide (CaO) %	Insoluble Residue (in HCl) %+ Calcium Oxide (CaO) %
1	Akbari Mahal Mughal Period	52.18	29.48	17.34	69.52
2	Akbari Mahal Sikh Period	65.61	11.85	21.54	87.15
3	Akbari Mahal British Period	48.24	37.35	12.41	60.65
4	Akbari Mahal Post-Independence Period	49.10	33.44	16.46	65.56

Table 03: *Wet Chemical Analysis of Lime Mortar Specimens, Royal Kitchen Lahore Fort*

S.No.	Description of Specimens	Insoluble Residue (in HCl) %	Mixed Oxides (Al_2O_3, Fe_2O_3, Ti_2O_3) %	Calcium Oxide (CaO) %	Insoluble Residue (in HCl) %+ Calcium Oxide (CaO) %
1	Royal Kitchen Mughal Period	40.13	40.11	18.76	58.89
2	Royal Kitchen Sikh Period	53.44	29.70	15.86	69.3
3	Royal Kitchen	60.59	16.80	21.61	82.2

4	British Period Royal Kitchen Post-Independence Period	58.77	10.65	29.58	88.35

Table 04: *Comparisons of the Wet Chemical Analysis of Lime Mortars of Similar Periods & Average Results*

Periods	Name of Monument	Insoluble Residue (in HCl) %	Mixed Oxides (Al_2O_3, Fe_2O_3, Ti_2O_3) %	Calcium Oxide (CaO) %	Insoluble Residue (in HCl) % + Calcium Oxide (CaO) %	Insoluble Residue (in HCl) % + Calcium Oxide (CaO) % (Average)
Mughal's	**1.Akbari Gate**	47.82	32.51	15.67	63.49	**63.96**
	2.Akbari Mahal	52.18	29.48	17.34	69.52	
	3.Royal Kitchen	40.13	40.11	18.76	58.89	
Sikh's	**1.Akbari Gate**	63.72	26.48	7.50	71.22	**75.89**
	2.Akbari Mahal	65.61	11.85	21.54	87.15	
	3.Royal Kitchen	53.44	29.70	15.86	69.3	
British	**1.Akbari Gate**	67.56	8.14	23.30	90.86	**77.90**
	2.Akbari Mahal	48.24	37.35	12.41	60.65	
	3.Royal Kitchen	60.59	16.80	21.61	82.2	
Post-Independence Period	**1.Akbari Gate**	66.50	16.23	16.50	83.0	**78.97**
	2.Akbari Mahal	49.10	33.44	16.46	65.56	
	3.Royal Kitchen	58.77	10.65	29.58	88.35	

3.2 Results of X-Ray Diffraction (XRD) of Lime Mortar Specimens

The X-Ray diffraction results of the lime mortar specimens are given below.

Table 05: ***XRD of Lime Mortar Specimens Akbari Gate Lahore Fort***

S No.	Description of Specimens	$CaCo_3$ %	Aggregates %	$CaCo_3$ Mineral Name	Aggregates Mineral Name	Others %
1	Akbari Gate Mughal's Period	35.61	Silicon Oxide SiO_2=19.57	-------	Low Quartz	Potassium Sodium Boron Phosphide $K_2NaB\ P_2$=44.81
2	Akbari Gate Sikh's Period	62.76	Silicon Oxide SiO_2=37.24	Calcite	Quartz	--------
3	Akbari Gate British Period	23.79	2-Thiohydantion $C_3H_4N_2OS$=28.51	Calcite	-----	2-Ureidopyridinium nitrate $C_6H_8N_4O_4/C_6H_7N_3O.HNO_3$=47.70
4	Akbari Gate Post-Independence Period	5.13	Silicon Oxide SiO_2=94.87	-------	Quartz low	---------

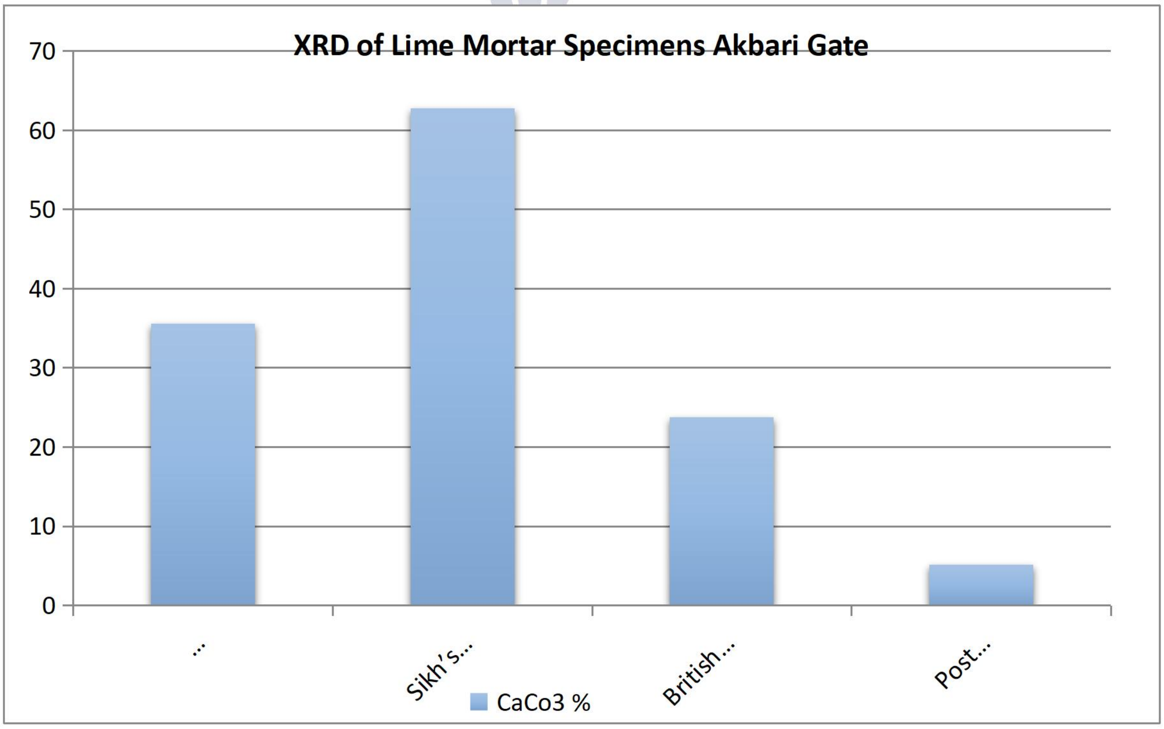

Figure 15: % of CaCO3 in Akbari Gate Lime Mortar by XRD

Table 06: *XRD of Lime Mortar Specimens Akbari Mahal Lahore Fort*

S No.	Description of Specimens	$CaCo_3$ %	Aggregates %	$CaCo_3$ Mineral Name	Aggregates Mineral Name	Others %
1	Akbari Mahal Mughal's Period	19.83	Lead Bismuth Vanadium Oxide Pb_4BiVO_8=50.84	Calcite	--------	Cadmium Mercury Tellurate $(Cd_{0.7}Hg_{0.3})_3Te_2O_9$=29.33
2	Akbari Mahal Sikh's Period	49.36	Silicon Oxide SiO_2=46.01	Calcite	Quartz	Lanthanum Barium Copper Tantalum Oxide $LaBa_2Cu_2TaO_8$=4.63
3	Akbari Mahal British Period	48.07	Silicon Oxide SiO_2=51.93	Calcite	Quartz	-------
4	Akbari Mahal Post-Independence Period	59.41	Silicon Oxide SiO_2=40.59	Calcite	Quartz	---------

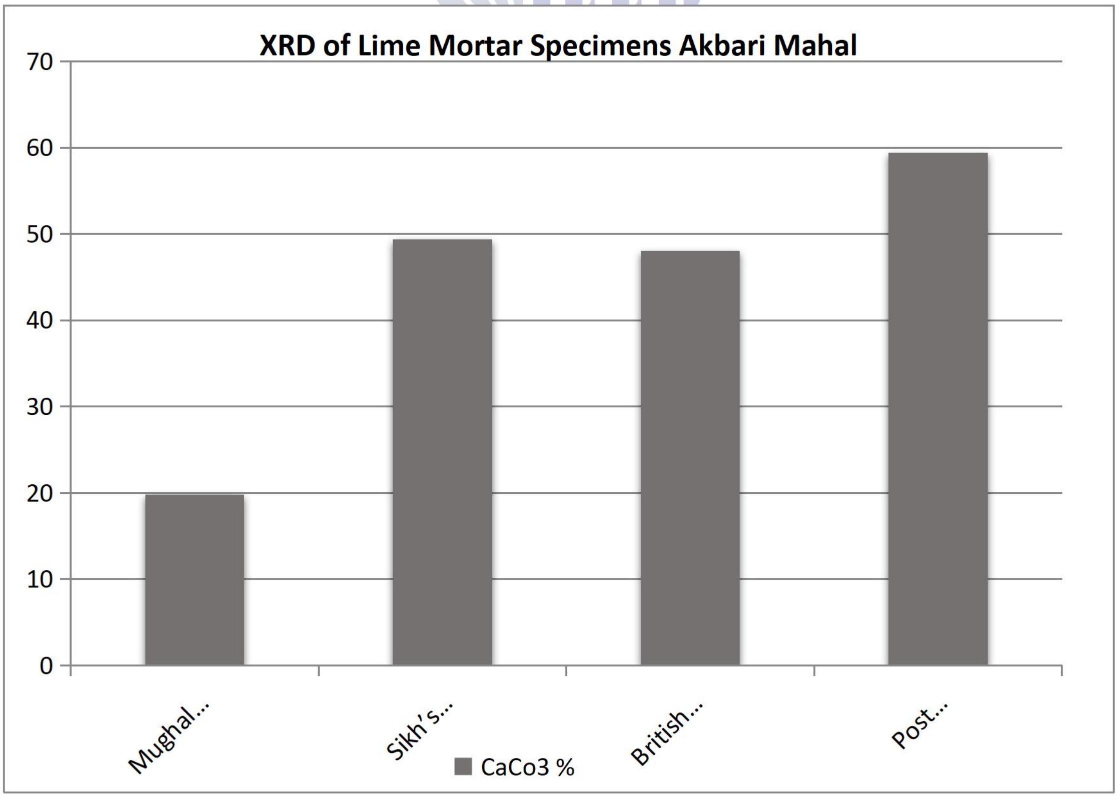

Figure 16: % CaCO3 in Akbari Mahal Lime Mortar by XRD

Table 07: *XRD of Lime Mortar Specimens Royal Kitchen Lahore Fort*

S No.	Description of Specimens	CaCo3 %	Aggregates %	CaCo3 Mineral Name	Aggregates Mineral Name	Others %
1	Royal Kitchen Mughal's Period	42.68	Silicon Oxide SiO_2= 33.22	Calcite	Quartz	Ammonium Molybdenum Oxide Hydrate $(NH_4)_2(Mo_3O_{10})H_2O$=24.10
2	Royal Kitchen Sikh's Period	51.31	Rubidium Magnesium Carbonate Hydrate$Rb_2Mg(CO_3)_2.4H_2O$=41.13	Calcite	---------	4-Cyanocinnoline $C_9H_5N_3$=7.56
3	Royal Kitchen British Period	46.80	Silicon Oxide SiO_2= 53.20	Calcite	Quartz	---------
4	Royal Kitchen Post-Independence Period	45.47	2 Thiohydantion $C_3H_4N_2OS$=52.04	Calcite	---------	Gallium Scandium Ga_2Sc =2.50%

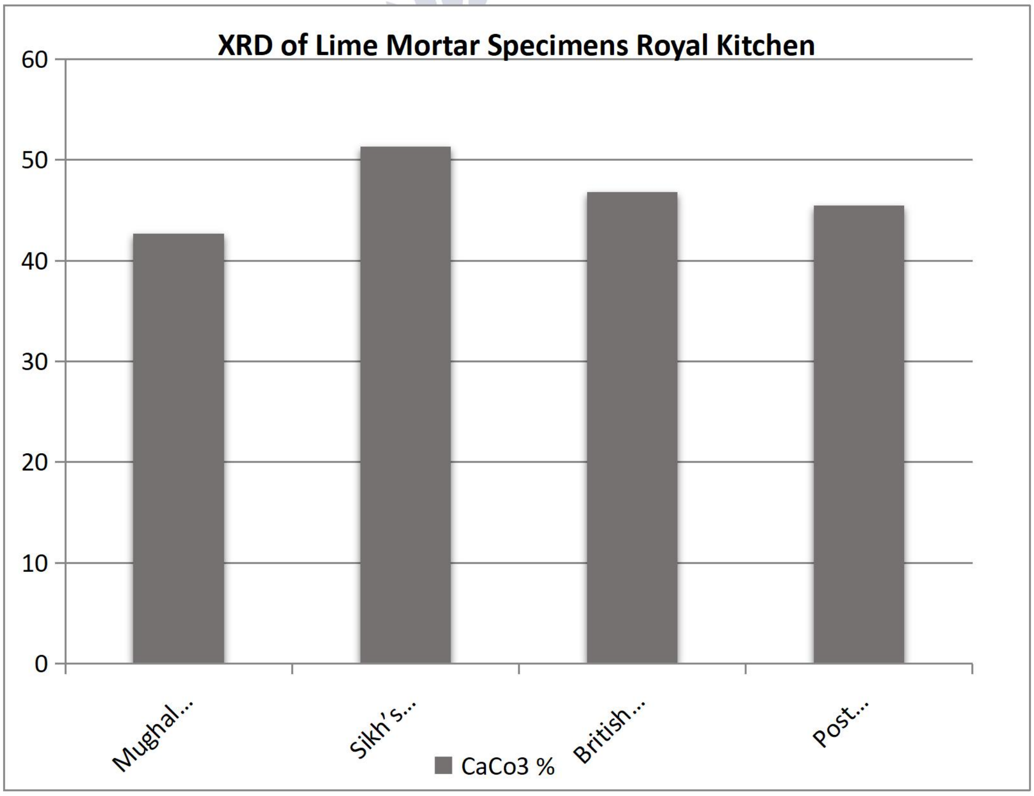

Figure 17: % CaCO3 in Royal Kitchen Lime Mortar by XRD

3.3 Results of Crushing Strengths of Lime Mortar Cubes Specimens

The results of the 14- day's crushing strengths of lime mortar cubes specimens are given below.

Table 08: *14-Days Crushing Strengths of Lime Mortar Cubes of Akbari Gate Specimen (Air Carbonation)*

S No.	Description of Specimens	Area ($inch^2$)	Load (Kg)	Load (lbs)	Crushing Strength (PSI)
1	Akbari Gate Mughal's Period	4	1451	3200	800
2	Akbari Gate Sikh's Period	4	1106	2440	610
3	Akbari Gate British Period	4	30	1200	300
4	Akbari Gate Post-Independence Period	4	152	336	z84

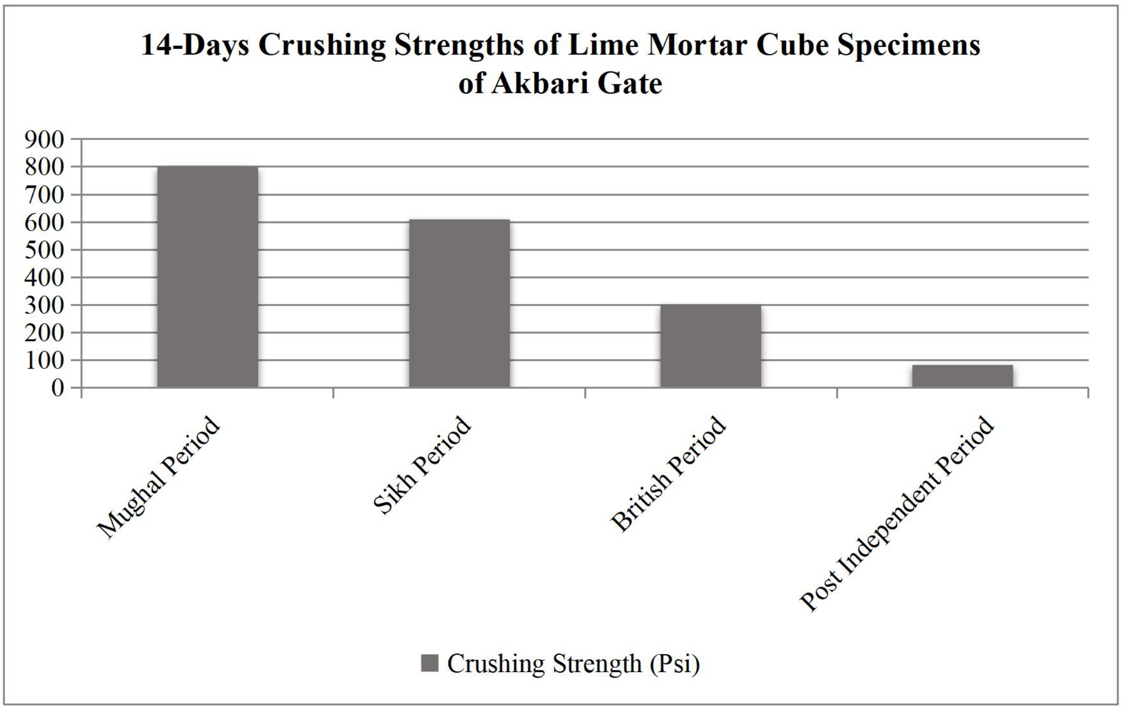

Figure 18: 14-Days Crushing Strengths of Lime Mortar Cube Specimens of Akbari Gate

Table 09: *14-Days Crushing Strengths of Lime Mortar Cubes of Akbari Mahal Specimens (Air Carbonation)*

S No.	Description of Specimens	Area ($inch^2$)	Load (Kg)	Load (lbs)	Crushing Strengths (PSI)
1	Akbari Mahal Mughal's Period	4	1115	2460	615
2	Akbari Mahal	4	1133	2500	625

	Sikh's Period				
3	Akbari Mahal British Period	4	426	940	235
4	Akbari Mahal Post-Independence Period	4	1270	2800	700

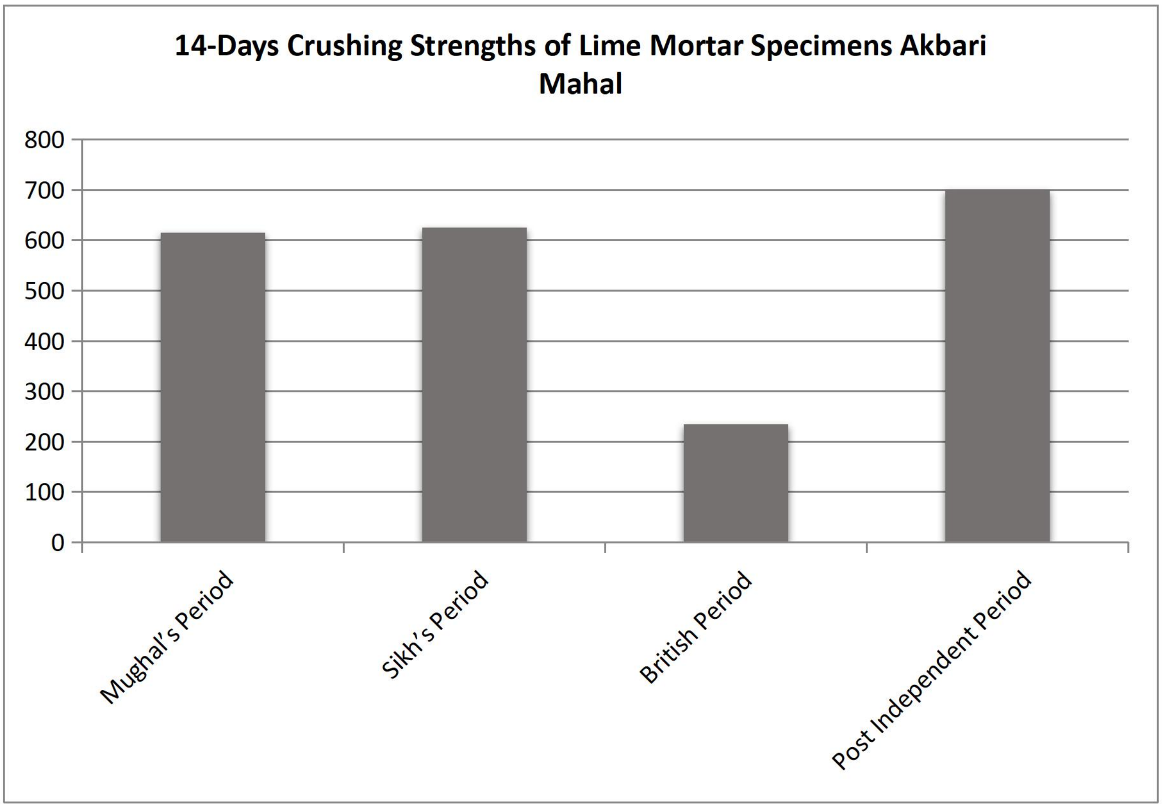

Figure 19: 14 Days Crushing Strengths of Lime Mortar Cube Specimen Akbari Mahal

Table 10: *14-Days Crushing Strengths of Lime Mortar Cubes of Royal Kitchen Specimens (Air Carbonation)*

S No.	Description of Specimens	Area (inch^2)	Load (Kg)	Load (lbs)	Crushing Strength (PSI)
1	Royal Kitchen Mughal's Period	4	1778	3920	980
2	Royal Kitchen Sikh's Period	4	1579	3480	870
3	Royal Kitchen British Period	4	635	1400	350
4	Royal Kitchen Post-Independence Period	4	1216	2680	670

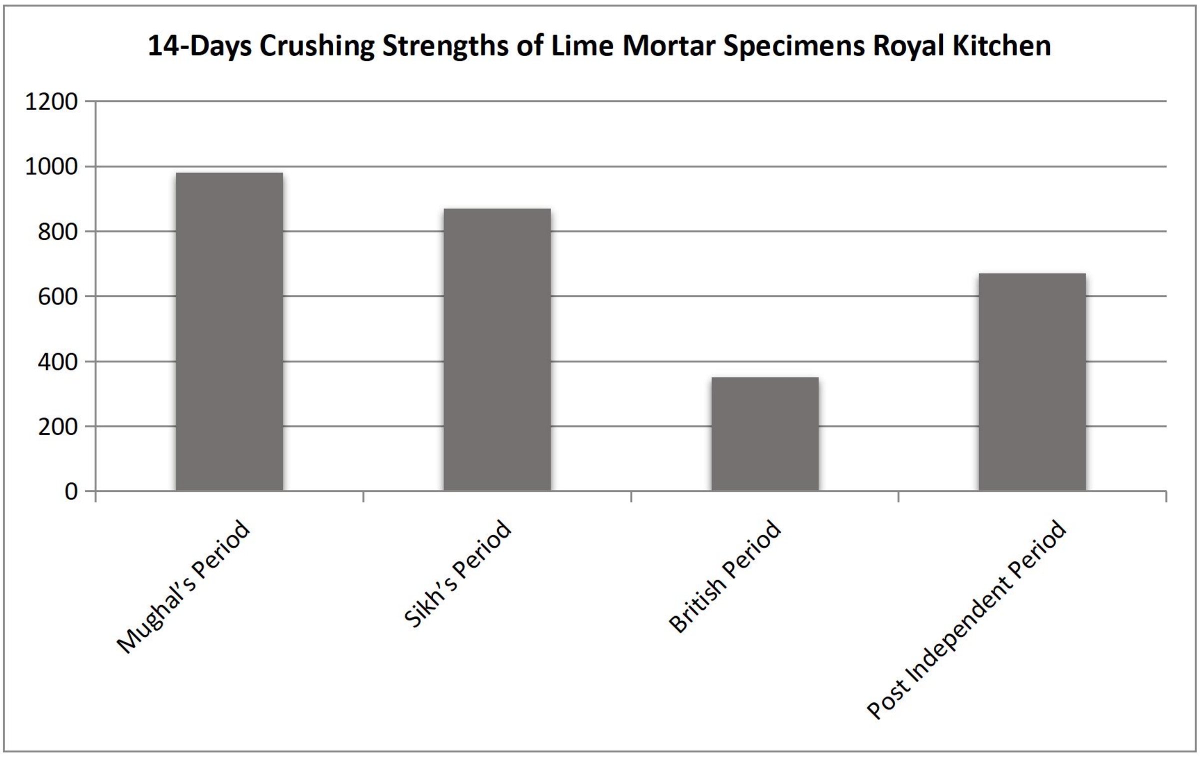

Figure 20: 14 Days Crushing Strengths of Lime Mortar Cube Specimen Royal Kitchen

4.0 Discussion

The wet chemical analysis and X-ray powder diffraction (XRD) of the lime mortar samples are complementary with support to each other. Both methods of analysis prove the existence of lime as one of the principal constituents of the majority of the specimens, except a few. The same has been observed in previous studies of wet chemical and XRD analyses (of historic lime mortars) relating to the complementary character of these two types of analysis (Ashurst and Ashurst, 1988; Elert et al., 2002).

The results of the XRD show that all the lime mortar specimens are characterized by different portions of calcium carbonate ($CaCO_3$), but the wet chemical analysis determines the presence of lime in the form of calcium oxide (CaO). This difference is attributed to the fact that it is in wet chemical analysis where heating is done, which causes the destruction of $CaCO_3$ into CaO resulting in the release of CO_2 and other volatile carbonates. Consequently, the proportion of CaO can be found much lower in wet chemical analysis, whereas the phases of crystalline $CaCO_3$ in the mortar matrix can be determined directly using XRD (Taylor, 1997; Moropoulou et al., 2000). The lack of sufficient lime and aggregate content is a major deficiency in the proportion of the lime and aggregates, which are observed in the majority of the specimens analyzed using the XRD procedure.

The $CaCO_3$ at Akbari Gate and the Royal Kitchen during the Mughal-period was reported to be 35.61% and 42.68%, respectively, meaning that there is a large deviation among the same period of history. Silica (SiO_2) was the main aggregate in both buildings and was in the form of sand and the percentages were 19.57% and 33.22%, respectively. This is a clear indication that a set lime-sand ratio was not always adhered to at the time of the Mughal, which has also been proven by earlier studies into Mughal building techniques (Asher, 1992; Khan, 2010).

By contrast, the Akbari Mahal Mughal specimens have a relatively low level of lime, and no sand aggregates may be identified. Rather, Lead Bismuth Vanadium Oxide was found in large amount (50.84%). It is understood to be the result of extended chemical reactions between the building blocks of the compound as opposed to a deliberate aggregate that was initially utilized by Mughal constructors. Aging-induced and environmentally induced mineralogical changes have also been observed in ancient mortars across all regions of the world (Elert et al., 2002; Moropoulou et al., 2005). Further evidence of the presence of post-depositional chemical alterations is seen in other secondary compounds which are present in other specimens.

Sikh specimens at Akbari Gate and Akbari Mahal have a greater lime content than Mughal specimens, but there is a big increase in the sand aggregates. The amount of sand in the Akbari Mahal specimen is almost equal to the amount of lime implying a change in methods of construction or repair during the Sikh period. But no sand was employed as an aggregate in the Royal Kitchen at this time; and Rubidium Magnesium Carbonate Hydrate was found 41.13%. This carbonate is known to improve the general stability and quality of mortar based on $CaCO_3$ (Moropoulou et al., 2000).

The specimens of British period show relatively high lime content but the sand ratio is too high in the specimens of the Akbari Mahal and Royal Kitchen giving an undesirable ratio of lime and sand. It is important to note that the Akbari Gate specimen dated to this period showed no evidence of sand aggregates which suggests the inconsistency in specifications of materials and workmanship (Ashurst and Ashurst, 1988).

The lime mortar that the Archaeology Department applies in their conservation interventions also has severe shortcomings in the aspect of proportionality. Though sand was a common aggregate material, immuno-reactive results showed the absence of sand in the Royal Kitchen specimen. In the specimen of the Akbari Gate a very bad proportion was found, some 5 per cent lime, and 95 per cent sand, and the Royal Kitchen specimen had about 60 per cent lime, and 40 per cent sand. These discrepancies are contrary to the internationally recognized principles of conservation which lay stress on the compatibility of materials and historical authenticity (ICOMOS, 1964; ICOMOS, 2003).

In general, these results indicate that there is a significant change in material specification in all historical periods, such as contemporary conservation works. The interviews conducted with a conservation chemist working at Lahore Fort also indicated that besides sand, a local calcareous clay called Kankar or locally referred to as Kasuri was also used as an aggregate. This material was found in a number of specimens, which prove that it was used by the Mughals and later constructors. Also, the existence of organic substances in Mughal and subsequent periodic mortars are in line with the reported traditional construction techniques that targeted to increase durability and strength (Khan, 2010; Moropoulou et al., 2005).

The quality of the lime mortar was not only determined after laboratory testing but also implied during the extraction of the specimen and the cube moulding. Mughal-period specimens and some of the Sikh and British specimens were very difficult to get out with considerable force with chisels and sludge hammers but Post-Independence specimens were easy to remove. These observations are supported by the cube moulding tests which showed that the specimen with greater carbonate content like calcium carbonate and rubidium magnesium carbonate hydrate has greater compressive strength. Moreover, the Mughal specimens with coarse aggregates and organic additives have good mechanical performance and those with low lime-sand ratios and without additives have low compressive strength (Moropoulou et al., 2000; Elert et al., 2002).

Literature analysis and visual findings also reveal that Mughal lime mortar joints were as thick as the bricks, and this tendency would add structural stability and strength. Instead, later levels of thickness in mortar joints have been brought down to a few millimeters, other than the interventions of recent conservation at Akbari Gate. These changes to original construction methods are the breach of the concepts of authenticity and integrity in international conservation charters, such as the Venice Charter and ICOMOS guidelines. Therefore, heritage conservation undertaken without these principles compromises the cultural and historical importance of the heritage buildings (ICOMOS, 1964; Jokilehto, 1999).

5.0 Conclusion & Recommendations

This concludes that variation in the scope of the percentage of lime and other constituents was because of the absence of technology and the absence of project management parameters in all the specimens prior to Post-Independence period. However, it is the same error that we are committing today when we are preparing the lime mortar without standardized proportions even though the technology has been much improved today.

The alteration of the percentage of lime and the various types of the experimental aggregates was the considerable cause of incompatibility of the old mortars to the new to cause the damages and corrosion of the heritage buildings. The lime mortar thickness that was nearly equal or even greater than the thickness of the brick has been brought down to several mm in the later times of the Mughals, which is not in line with ethics of conservation as stated in the ICOMOS and at Venice Charter.

It is evident through the study that the original mortars of the Mughals and a specimen of even Sikh period, where with lime some other natural additions were made, are stronger than all others not containing such natural additions. The lab results of crushing strength not only justify this argument but also physical experience of the author regarding the extraction of lime mortar.

Therefore, it is advised to the Archaeology department to prepare a work breakdown structure (WBS), prior to any conservation work in future. First of all, using this WBS, the investigation into the ingredients of the materials (lime mortar) that was used in different periods should be conducted. In this respect, chemists and engineers can be crucial. The new mortars should be prepared as per the original one used by Mughals adding natural additives and aggregates as per the proportion in the laboratory tests. In the long run, the cost of rework of conservation activity as a result of repetition would be significantly lower once hierarchy of WBS is established and consequently quality and life of the heritage buildings would be improved.

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