been located associated with granite mylonite, and leucosome of migmatite in shears parallel to those found in Devri area. At Devri, the mineralized part of bore hole core shows intense shearing and mylonitization and fracture-filling by calcite. The bore hole data accrued so far show several intercepts of mineralization associated with sheared granite and pegmatite, which are mylonitized, ferrugenized and calcite-rich. In addition to Devri occurrence, mineralization may extend further south towards Godkatwa and Chandaura; parallel shears are intercepted and the grade and thickness improve at the subsurface. As most of the area is soil-covered and used for rice cultivation and there are meagre outcrops, geophysical surveys can help in the exploration by tracing the shear zone in the subsurface, as has been observed in the bore holes drilled in Devri area. To confirm this fact, geophysical surveys (gravity, magnetic and resistivity) need be carried out in the Devri, Chandaura Darhora and Pakni sectors (Figure 1), so that parallel shears can be traced and the signature of alteration pattern can be perceived.

It is inferred that initial phase of uranium mineralization is intrinsically associated with various rock types, including migmatites. Later it got mobilized during folding episodes and emplacement of granite and became concentrated in shears zones, which facilitated fluid movement. The block of Devri–Darhora–Pakni, which does not have much surface expression of mineralization, may add to uranium resource potential of SCB.

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Bricks and mortars in Lucknow monuments of c. 17–18 century

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Lucknow monuments which date back to 17–18th century are large masonry structures built using thin burnt-clay bricks (*lakhauri*) and lime-crushed brick aggregate (*surkhi*) mortars. Studies were carried out to characterize engineering properties of old masonry materials and new mortars being used for the renovation work. Mechanical properties of reclaimed *lakhauri* bricks were found comparable to good-quality contemporary bricks of the neighbouring region. Moreover, XRD and SEM–EDS analyses indicated that mineralogical composition is not too different, except few minerals. The lime–*surkhi* mortar used in old masonry work was found to be lime rich with binder to aggregate ratio of about 1 : 2 to 3 by volume and is similar to those used in Byzantine structures of Western and Central Asia. The renovation mortar had poor hydraulic property compared to old mortars indicated by TG–DTA analyses.

Keywords: Bricks, chemical physical studies, historical mortars, Lucknow monuments.

HISTORICAL buildings and monuments are a part of cultural heritage and worth preserving. Therefore, civic societies and governmental agencies should pay more attention to their maintenance and preservation to protect them for the enjoyment of future generations. Lucknow monuments are hallmarks of 17–18th century Awadhi architecture of northern India, which are a kind of masonry structure of grand proportions. These large masonry structures were built using locally made thin burnt-clay bricks (*lakhauri*) and lime-crushed brick aggregate (*surkhi*) mortars. Two of the most prominent structures of this period are: (a) *Bada Imambara* (*Imambara of Asaf-ud-daula*) and (b) *Rumi Darwaza*, a Romanesque gateway leading to the Imambara Complex (Figure 1)[1].

Work at Rumi Darwaza was taken up recently by the Archaeological Survey of India (ASI), Lucknow, to repair the damage developed in the structure because of ageing, climatic conditions and vibration due to traffic movement through the gate. No significant retrofitting or intervention work was carried out, though there were major cracks found in the structure. The current status of the Rumi Darwaza and the intervention work is shown in Figure 2.

Studies on the material characterization of historical masonry materials and structural analysis of the historical

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monuments are the important aspects of any renovation or retrofitting of ancient structures. The most important aspect considered in the renovation works of historical buildings is that the intervention material should be compatible with the original material in the sense that it will not cause any damage in the long term. This requires knowledge about the physical properties, mineralogical and chemical composition of original masonry materials as well as various problems arising out of continued deterioration.

Use of wrong materials in the restoration of historical buildings leads to rapid deterioration in the whole building and its constituent elements. In addition, they may lose their historical, documental and aesthetical value. The materials used in restoration are usually selected without carrying out detailed research and without determining what problems they may cause, leading to undesirable effect on the structure in short and long-term, as also observed by Manzoni *et al.*[2]. It is important that suitable criteria should be adopted for the selection of repair mortars considering the requirements of resistance to the environmental conditions as well as of compatibility to old materials[3].

Lucknow monuments use thin burnt clay bricks (*lakhauri*) and lime-crushed brick aggregate (*surkhi*) mortars. Lakhauri bricks are flat, rectangular bricks with typical sizes of 100 mm × 150 mm × 20 mm and 100 mm × 150 mm × 50 mm. The crushed brick aggregate was used with lime for mortar preparation which has great influence on its final strength, as *surkhi* also acts as a hydraulic binder to some extent. The thickness of horizontal and vertical mortar joints are about 20–30 mm and 10–20 mm respectively, in various Lucknow monuments. The crushed brick and lime mortars and plasters have been extensively used in Byzantine and post-Byzantine structures and earlier research indicate that factors such as mix ratio, lime preparation technique, crushed brick grain size distribution and texture are necessary for proper simulation of traditional mortars.

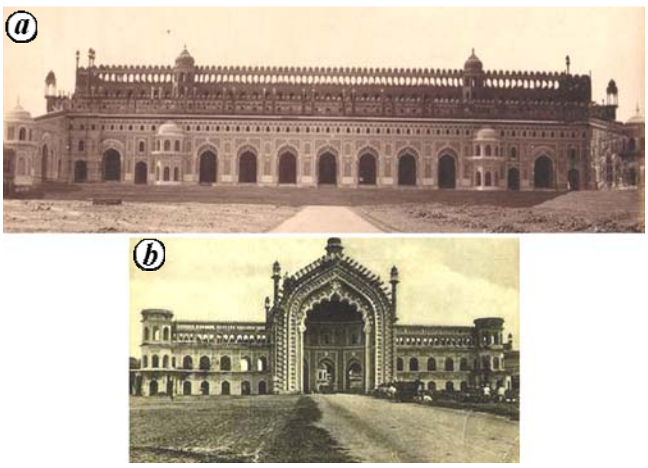

Figure 1. ***a***, Bada Imambara (Imambara of Asaf-ud-daula); ***b***, Rumi Darwaza.

Bricks, mortars and plaster samples were collected from various sites of Lucknow monuments and renovation plaster sample was collected from Rumi Darwaza and other structures such as Dilkhusha and Naubatkhana. The test methods such as microwave acid digestion, thermo-gravimetric analysis (TGA), scanning electron microscope associated with energy dispersive spectroscopy (SEM–EDS) and X-ray diffraction (XRD) were used to find the chemical and mineralogical composition of bricks, mortars and plasters.

The brick samples collected from Lucknow monuments were examined visually for their surface texture, colour, particle shape and size. Photographs of the representative brick samples from Imambara Complex, Naubatkhana, Dilkhusha-1 and Dilkhusha-2 are shown in Figure 3. The renovation plaster samples were collected from Rumi Darwaza to check the compatibility of the renovation mortar with the existing mortar.

SEM–EDS was used to identify the topography, morphology, composition and crystallographic information of the brick samples. The microscopic images of Imambara Complex and contemporary brick samples obtained from SEM–EDS analyses are shown in Figure 4.

From the analysis, it was found that the *lakhauri* bricks contain high amount of quartz (SiO_2), aluminium oxide (Al_2O_3), ferric oxide (Fe_2O_3) and traces of albite, magnesium oxide (MgO), titanium oxide (TiO_2) and calcium oxide (CaO) (Table 1). The percentage of calcium carbonate ($CaCO_3$) is high in Dilkusha-2 bricks and the presence of $CaCO_3$ reveals the existence of charcoal and lime. This brick is suspected to be not well-burnt, since $CaCO_3$ will be decomposed into CaO and CO_2 at temperatures more than 840°C, and the same is supported by visual examination (yellowish-red colour) of the brick. Titanium oxide and wallostanite were found in the *lakhauri* bricks, which are commonly used in refractory bricks to perform better under high-temperature condition and provide more resistance to cracking and spalling. The historical bricks of Lucknow monuments contain silica on an average of 60%, which showed that the bricks used for the construction of these monuments were of good quality.

The bulk mineralogical composition analysis was performed using XRD method on *lakhauri* bricks. The XRD patterns of Dilkhusha-1 brick and contemporary brick samples are shown in Figure 5. Quartz, feldspar, Fe_2O_3 and Al_2O_3 were found to be the major minerals in the brick sample. The presence of hematite shows that the firing temperature of the bricks was around 850°C, since hematite will be the derivative of calcium-poor clays at high temperature.

The XRD pattern does not contain any peaks for calcite, which reveals that calcium-poor clay was used for the manufacture of the bricks. Other than major minerals, TiO_2, MgO, chlorite and manganese oxides were also

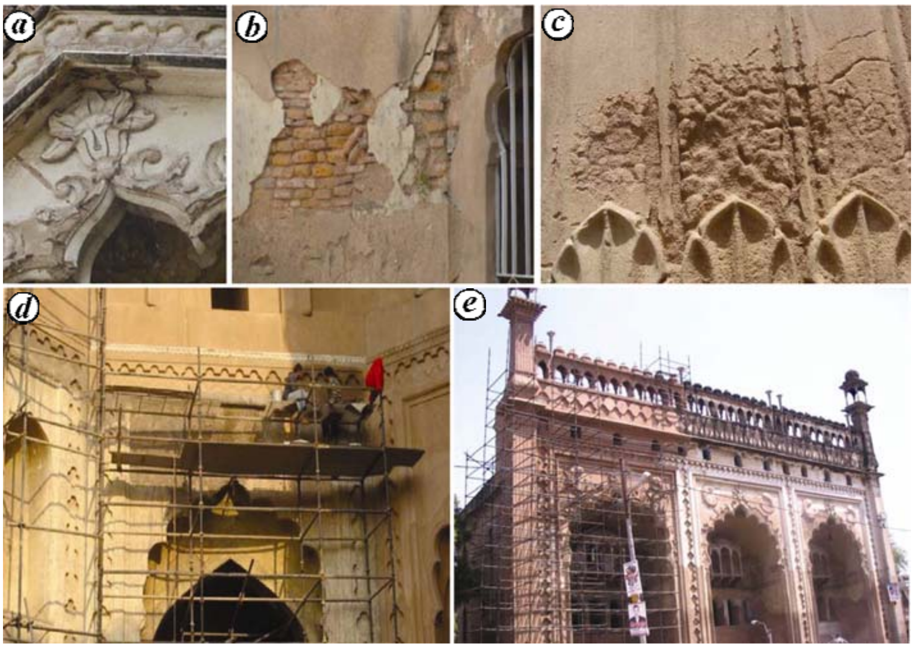

Figure 2. ***a***, Major cracks at the crown of the arch. ***b***, Spalling of plaster from the walls. ***c***, Deterioration of recent renovation work carried out at Naubatkhana. ***d***, Renovation at Rumi Darwaza. ***e***, Renovation at Naubatkhana.

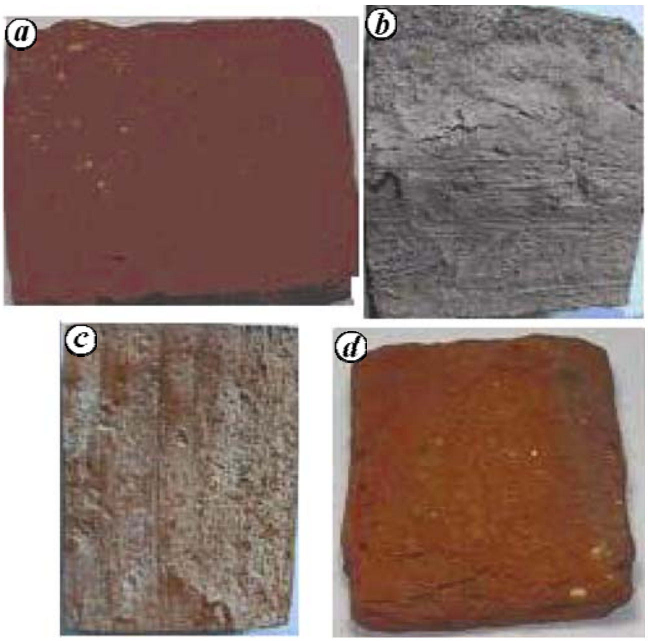

Figure 3. Representative brick samples. ***a***, Imambara Complex; ***b***, Naubatkhana; ***c***, Dilkhusha-1 and ***d***, Dilkhusha-2.

found in traces. The XRD spectrum of existing and renovation *surkhi* samples was the same and, hence, it can be concluded that the firing temperature of the bricks could be similar.

The basic physical properties of apparent density, real density, water absorption, porosity and initial rate of absorption were determined (Table 2). These properties are important in order to assist in mortar selection and material handling in the construction process. The rate of absorption can have an important effect on the interaction between freshly laid mortar and the brick units and subsequently on masonry bond strength. Typically, the initial rate of absorption (IRA) values between 0.25 and 1.5 kg/m^2/min produce good bond strength with compatible mortar. The average value of water absorption (WA) and IRA of brick samples collected from Lucknow monuments was 11.3% (coefficient of variation (COV) 54%) and 2.8 kg/m^2/min (COV 60%) respectively. The COV is significant as the samples come from different monuments of a construction period of 17–18th century *Awadhi* architecture.

The uni-axial compressive strength test of the bricks was performed according to ASTM C 67 (ref. 4). Since the bricks collected were not of standard dimension, they were cut into approximately same size and the surface was levelled by grinding and capping. The compressive strength (f_b) and modulus of elasticity (E) values are summarized in Table 2. The average compressive strength of *lakhauri* bricks is 15.0 MPa (COV 16%) and modulus of elasticity is 5.7 GPa (COV 50%). The average value of 380 for E/f_b obtained from compressive strength test of *lakhauri* bricks compare well with the average value of 300 obtained for contemporary bricks by Kaushik *et al.*[5].

Visual examination showed that the aggregates used in existing and renovation mortars or plasters mainly contain bricks and quartz mineral, and the aggregates were sub-angular and round in shape. Photographs of samples

Table 1. Elemental composition of *Lakhauri* bricks

Sample location	Mineral composition (%)										Visual inspection	Hue and Chroma
	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	Na_2O	TiO_2	MgO	MnO_2	CaO	Wallotanite		
Imambara Complex	60.1	21.1	3.2	13.0	1.2	2.8	1.4	–	–	15.3	Dark red	2.5 YR 3/8
Naubatkhana	58.6	15.0	13.6	10.0	1.8	2.1	1.0	0.4		16.1	Reddish-brown	2.5 YR 4/3
Dilkusha-1	68.6	19.4	9.0	–	1.4	1.1	1.0	–	0.6	–	Red	2.5 YR 4/8
Dilkusha-2	38.9	13.4	4.8	40.3	1.4	–	1.1	–		–	Yellowish red	5 YR 4/4
Contemporary brick	66.2	21.1	8.6	–	1.8	1.3	1.2	–	1.0	–	–	5 YR 6/8

Table 2. Summary of test results of *lakhauri* bricks collected from Lucknow monuments

Sample location	Apparent density (g/cc)	Real density (g/cc)	Water absorption (%)	Porosity (%)	IRA ($kg/m^2/min$)	Compressive strength, f_b (MPa)	Modulus of elasticity, E (GPa)
Imambara Complex	1.7	2.2	11.4	19.9	2.7	14.6	3.8
Naubatkhana	1.9	2.1	5.1	9.7	1.2	12.9	4.4
Dilkhusha-1	1.8	2.5	13.7	25.2	3.5	24.5	5.4
Dilkhusha-2	1.7	2.4	17.3	29.2	4.6	17.6	9.0
Average	1.8 (6)*	2.2 (7)	11.3 (54)	19.6 (50)	2.8 (60)	15.0 (16)	5.7 (50)
Contemporary brick	1.8 (4)	2.4 (0.8)	12.3 (0.1)	32.9 (16)	1.9 (0.3)	20.8 (0.3)	6.1 (0.3)

*Values in parenthesis indicate percentage of coefficient of variation.

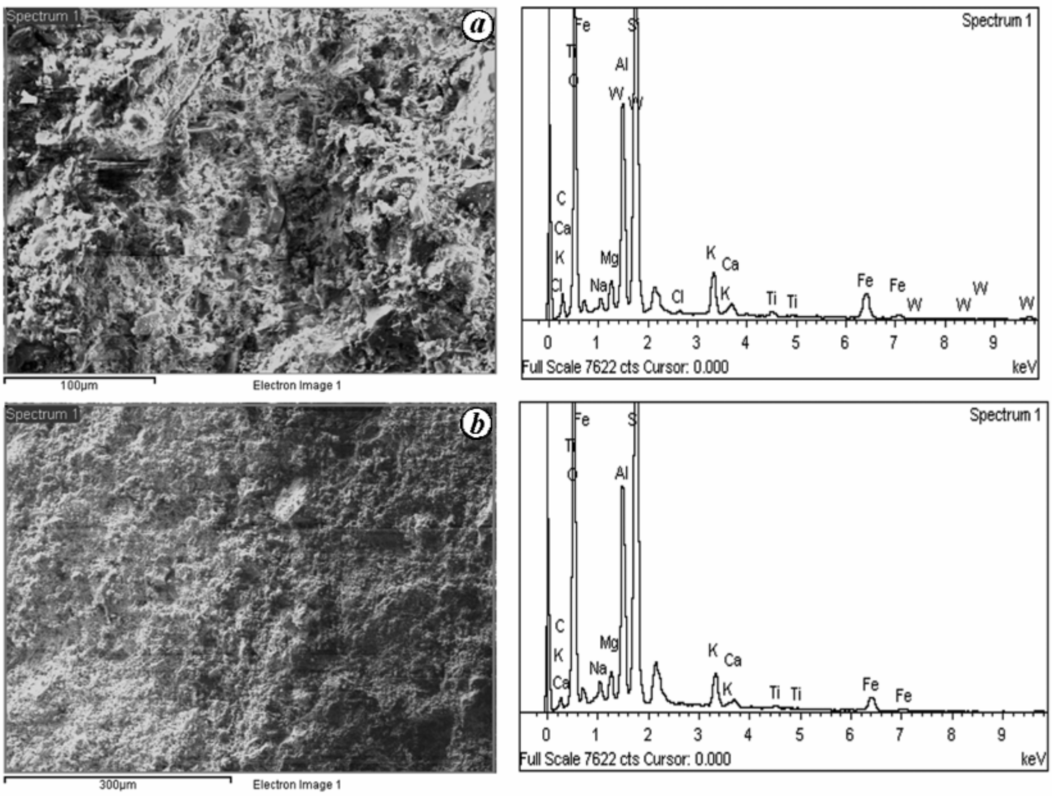

Figure 4. SEM backscattered image and EDS spectrum of (***a***) Imambara Complex and (***b***) contemporary brick.

are shown in Figure 6 and colour of mortar samples from different locations is listed in Table 3. It is clear that the colour of the renovation mortar at Rumi Darwaza is different from existing mortar.

Binder–aggregate ratio and the particle size distribution of the aggregates were determined using microwave digestion system (VERSAL V-800) in order to know the raw material composition of mortars and plasters.

Binder–aggregate ratio in terms of volume proportion was calculated based on the unit weight of lime, *surkhi* and sand used for renovation mortar at Rumi Darwaza.

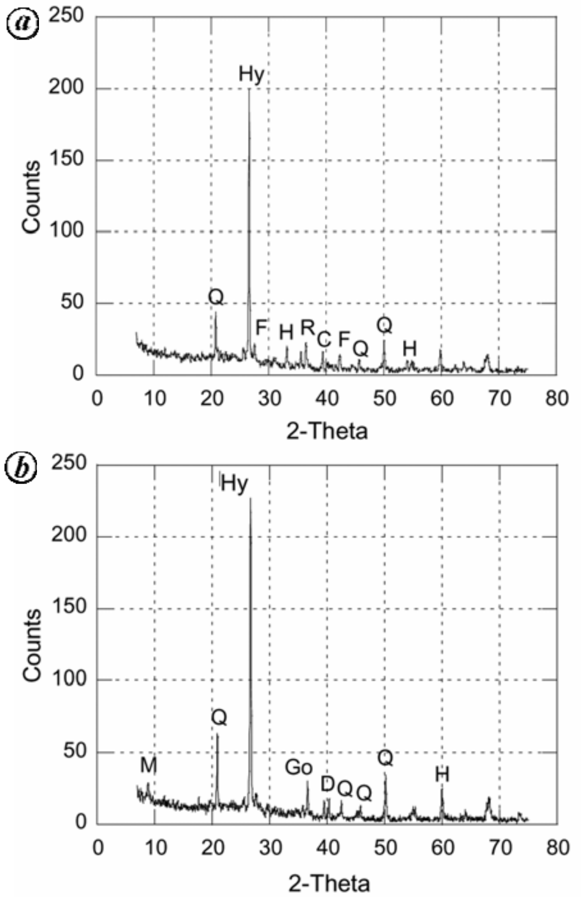

Figure 5. XRD pattern of (***a***) Dilkhusha-1 and (***b***) contemporary brick. Q, Quartz; Hy, Halloysite; F, Feldspar; H, Hematite; C, Calcite; R, Rulite; M, Mica; Mu, Muscovite; Go, Goethite; D, Dolomite.

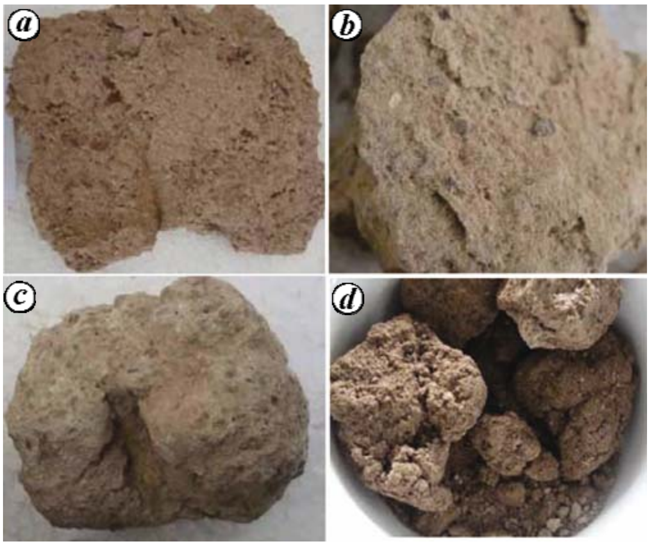

Figure 6. Representative mortar samples. ***a***, Imambara Complex; ***b***, Naubatkhana; ***c***, Moosa Bagh; ***d***, Rumi Darwaza.

From Table 4 it can be concluded that the old mortars were lime rich with lesser aggregate content (1.5–2.0 times the binder content), which is supported by Chandra[6] and was also found in historical mortars in Hagia Sophia, Turkey[7]. It should be emphasized that these mix ratios in historic lime mortars are different from typical 1 : 3 ratio for binder to aggregate in mortars.

In addition, it was observed that in the renovation mortar, the aggregate to binder ratio is high (about 3.0–3.3) compared to historical mortars and plasters (about 1.5–2.0). In other words, the binder (lime) content is much less in renovation mortar compared to the historical mortar. The lime deficient mortar leads to poor bond, poor workability, poor water retentivity and less elasticity of the mortar and, most importantly, it is different from the historical mortar. Thus, these lime deficient mortars are clearly not suitable for the renovation/repair work of the Lucknow monuments.

Thermogravimetry with differential thermal analysis (TG–DTA) was carried out on mortar and plaster to characterize the hydraulic property of samples using Perkin-Elmer Pyris 6 Thermo-Gravimetric Analyzer with PYRIS software. From the TGA analysis, it was found that the mortar used for renovation purpose at Rumi Darwaza is non-hydraulic, whereas the historical mortars are hydraulic (Table 5). According to Moropoulou *et al.*[8], the mortars will be hydraulic if CO_2 is more than 3% and H_2O is less than 30%. Thus, the renovation mortar used at Rumi Darwaza was not suitable because hydraulic mortars are essential. Hydraulic mortars set faster, have less shrinkage cracks and low modulus of elasticity. Hence they are extremely flexible and allow for thermal expansion, without significant thermal strain.

The field test was also performed on lime used for both formulated mortar and renovation mortar using hydrochloric acid to verify its hydraulic properties and to know the class of lime used. The renovation lime formed a flowy gel indicating feebly hydraulic and Class-C lime, whereas hydrated lime used for formulated mortar resulted in thick gel indicating highly hydraulic and class-A lime.

The bulk mineralogical composition analysis was performed using XRD on fines (grain size less than 75 microns) of mortar or plaster samples obtained after acid digestion. XRD pattern of Naubatkhana and renovation mortar sample is shown in Figure 7.

Quartz (Q), albite (A), kaolinite (K), feldspar (F), calcite (C), dolomite (D) and illite (I) are the main minerals observed from the fines of mortar samples. Calcite was found in mortar samples in traces since most of the calcium content was digested in the acid digestion process itself. All the mortar samples showed XRD peak for kaolinite clay mineral. However, the renovation mortar had a peak for illite clay mineral. From the analysis, it was found that the mortar samples differed only in the presence or absence of trace amounts of a few minerals.

Table 3. Munsell standard colour for historical mortar

Mortar sample	Structural use	Colour	Hue and chroma
Naubatkhana	Joint mortar	Light reddish-brown	2.5 YR 7/4
Imambara Complex	Plaster	Pink	7.5 YR 7/3
Moosa Bagh	Joint mortar	Pale brown	10 YR 7/3
Renovation mortar	Plaster	Brown	10 YR 5/3

Table 4. Aggregate–binder ratio of historical mortar and plaster

		Aggregate/binder (weight proportion)		Aggregate/binder (volume proportion)	
Period	Sample location	Detecting moisture	Without detecting moisture	Detecting moisture	Without detecting moisture
Historical	Naubatkhana	2.63	1.83	2.98	2.07
	Imambara Complex	2.44	2.00	2.47	2.03
	Moosa Bagh	1.71	1.52	1.89	1.68
Renovation	Rumi Darwaza	3.67	3.00	4.03	3.30

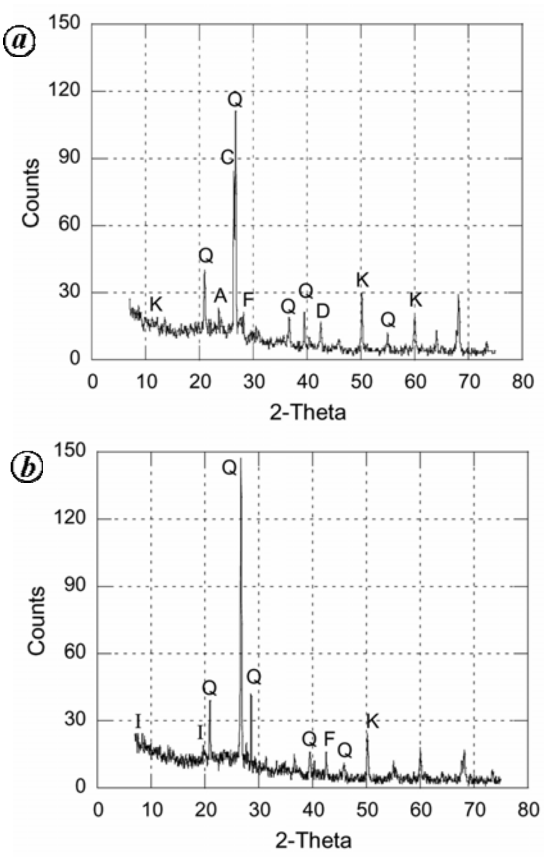

Figure 7. XRD pattern of mortar sample. ***a***, Naubatkhana; ***b***, Renovation mortar at Rumi Darwaza. Q, Quartz; A, Albite; K, Kaolinite; F, Feldspar; C, Calcite; D, Dolomite and I, Illite.

The lime–surkhi mortar was simulated in the laboratory based on the mortar proportion and aggregate fraction used in various historical monuments and also based on the mortar proportion obtained from chemical analyses of the samples collected from the Lucknow monuments. Compressive strength test was performed on standard lime–surkhi mortar cubes according to IS:2250 (ref. 9). Compressive strength of 28 days was 1.71 MPa under normal condition.

Particle size distribution of the aggregate was determined by sieve analysis, according to IS:3182 (ref. 10). In existing mortars and plasters, brick bats (broken pieces of bricks) were used as aggregates along with sand. For the mortar of Imambara Complex and the renovation plaster mortar of Rumi Darwaza, particle size varied from 1.18 mm to fines (< 75 μm). The aggregates were well graded for the Imambara Complex mortar and uniformly graded (poorly graded) with higher percentages of a few grain sizes for the renovation mortar. In Naubatkhana and the Moosa Bagh mortars, the particle size ranged from 4.75 mm to fines (< 75 μm) and the aggregates were poorly graded (Figure 8). The grain size distribution of renovation mortar is comparatively similar to that of the ancient mortar. However, the percentage of fines is very low and percentage of medium sand is very high.

The mineralogical, physical and mechanical properties of *lakhauri* bricks and historical mortars were determined using experimental techniques, such as optical microscopy, X-ray diffraction, thermogravimetry, microwave acid digestion, etc. These results were then compared with the corresponding values of contemporary bricks and renovation mortar to know the quality of renovation work done at various sites of historical importance in Lucknow.

The mineralogical study using SEM and XRD method showed that quartz, feldspar, aluminium and iron oxide are the major minerals present in the *lakhauri* bricks. The *lakhauri* bricks had IRA in an acceptable range however, significant number of bricks were observed to have high IRA values indicating that they require to be pre-soaked before laying and sufficient curing is required after laying. The average compressive strength of *lakhauri*

Table 5. TGA analysis

Period	Samples	% CO_2	% H_2O	% CO_2/% H_2O	Remarks
Historical	Naubatkhana	6.03	12.29	0.49	Hydraulic
	Imambara Complex	13.40	9.83	1.36	Hydraulic
	Moosa Bagh	13.49	3.97	3.40	Hydraulic
Renovation	Rumi Darwaza	1.78	1.61	1.11	Non- Hydraulic

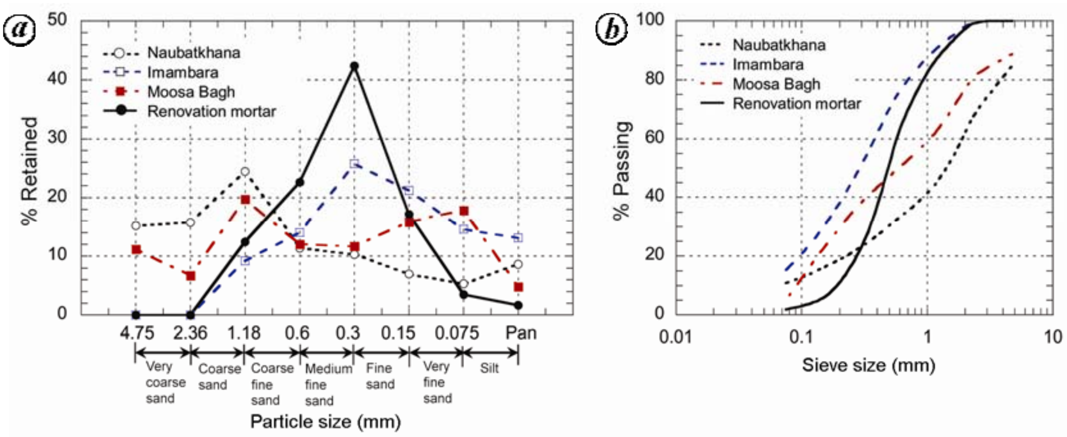

Figure 8. ***a***, Particle size distribution of aggregate. ***b***, Aggregate gradation curve.

bricks collected from Lucknow monuments was 15.0 MPa and the modulus of elasticity was 5.7 GPa. The compressive strength of *lakhauri* bricks was found to be as high as of contemporary bricks available in North India.

From microwave acid digestion test, it was found that the renovation plaster used at Rumi Darwaza had different proportions of aggregate and binder than the historical mortar and also the aggregates were graded uniformly with high percentage of medium sand. The old mortars were lime rich with lesser percentage of aggregate content, whereas the renovation mortar had lesser binder content with more percentage of medium sand. The TG–DTA analyses revealed that the historical mortars and plasters were hydraulic in nature, however, the mortar used for renovation work was not hydraulic and may have been responsible for the rapid deterioration of renovation plaster in the repair work at Naubatkhana.

Though *lakhauri* bricks appear to be no different from contemporary bricks, the mortars used in Lucknow monuments are considerably different than mortar mixes used today for brickwork. These old mortars are not only lime rich and had a large binder to aggregate ratio, but the lime present possesses hydraulic properties. It is important that materials used for renovation work should be compatible and similar to the original material used in the historical structures.

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