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DWELLING THE HERITAGE: CHARACTERIZATION OF LIME MORTAR AND BRICKS USED IN FOREST RESEARCH INSTITUTE, UTTRAKHAND, INDIA

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Abstract

Conservation of historical buildings has socio-economic impact and in order to conserve historic structures without disturbing its aesthetics, a precise characterization of raw materials is very much essential. In the present paper, the historical structure, Forest Research Institute (FRI), Dehradun, Uttarakhand, India, has been investigated as it is known as remarkable masonry structures using red bricks and lime mortar systems. Different samples of mortar and bricks of the building were analysed using different techniques such as Optical microscopy, X-ray Diffraction (XRD), Field emission scanning electron microscopy coupled with energy dispersive (FE-SEM/EDX), X-ray spectroscopy (XRD), Thermo Gravimetric Analysis (TGA) and Infrared Spectroscopy (FT-IR). The analysis shows that bricks are made up of non-calcareous clay material and firing temperature was not exceeding above 900°C.
All the brick samples analysed in this study have the water absorption, porosity and bulk density in the range of 10.9-18.5% , 15.5-32.2 % and 1.66-1.96 g/cm^3, respectively, while the compressive strength of all the brick samples is found to be in the range of 7.8-14.2 MPa. Mortar samples are stiff, compact and hydraulic due to the presence of surkhi and brick aggregates. The petrological analysis revealed the presence of calcite and quartz, which is also confirmed by XRD and FE-SEM/EDX analysis. SEM micrographs shows needle-like structure of calcite mineral indicates the complete carbonation of the lime. Further, FTIR results indicating the use of organic admixtures in the buildings mortar samples.

Keywords: *Lime mortar; Brick; Heritage Building; Characterization; Conservation*

Introduction

Remedial interventions of heritage structures using compatible material meant for material deterioration and structural distress caused by natural, environmental, or human intrusions is the need of today. For developing a compatible material, we must know about the materials used in the ancient structures and hence, the characterization of materials used will be the first step to achieve this role [1]. Characterization of material used in historic buildings not only provided us the in-depth knowledge about the methodologies and techniques, but it also gives detailed information about the role of these materials used [2]. Furthermore, a proper understanding of physico-chemical, mineralogical composition including mechanical and physical properties through précised characterization has been recognized as essential for archaeologists, researchers and conservationists working in the field of heritage building conservation and restoration [3]. Characterization of ancient mortars involves the analysis of

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micro-structures as well as mineralogical composition in order to get the detailed information of binder, aggregates and additives used for the preparation of mortar [4].

The bricks or stones used in historical monuments of India generally relied on lime, mud/clay, and gypsum binders in a mortar and plaster, which was technically called ancient, historical or traditional mortar or plaster. The application of lime with sand and other pozzolanic materials like bricks, stone fragment or marble dust has a long and successful history in ancient building construction [5-7]. The crushed or finely ground brick with lime mortar and plaster has been used all over the world and known by different names i.e. Horasan in Turkey, Homra in Arabic, Cocciopesto in Roman and Surkhi in India [8]. Available literature reveals that mortar and plaster mix prepared with crushed and ground bricks provide high mechanical and flexural strength along with good setting properties with water [9].

In surkhi, aluminosilicates are present in an amorphous form which on reaction with lime in the presence of water results in the formation of calcium-silicate-hydrate and calcium alumino silicate hydrate, these hydraulic products formed at the brick limes matrix and the pores of the bricks (Fig. 1). So, when surkhi is added in lime to prepare mortar mix interlocking hydraulic crystals formed which gives mortar a hydraulic set and improves the strength which, in turn, justifies their use in the construction of many historic buildings since ancient times [10].

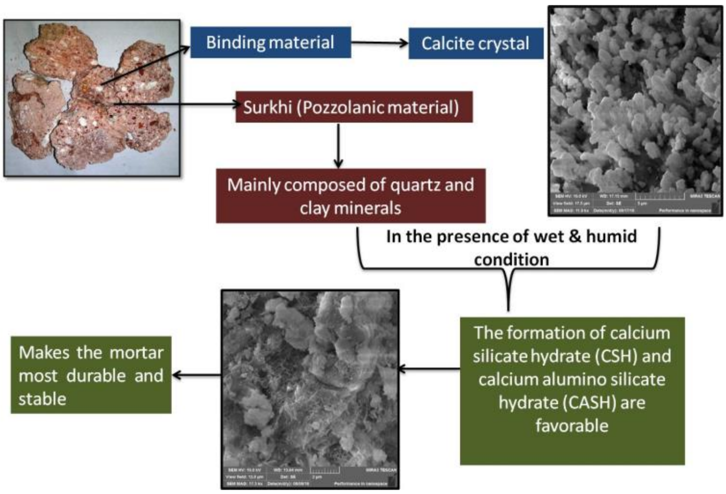


Fig. 1. Mechanistic presentation depicting the role of lime and surkhi in ancient mortar

Fig. 2. General view of FRI, building, Dehardun

For the restoration work, applied mortar and replaced brick must be compatible with the original mortar in terms of chemical, physical, mechanical properties, and aesthetics. It has been proved that the use of cement-based mortar accelerates the masonry decay due to the non-compatibility with the ancient building materials [11-13].

In the present study, an attempt has been made to characterize the mortar and brick samples from the building of Forest Research Institute, Dehradun (Fig. 2) for the first time. The collected mortar and brick samples were analyzed on the basis of physical, mineralogical and microstructural compositions that can be used to develop a compatible material in future for the restoration purpose of the mortar and bricks.

Building Background

The Forest research Institute was established as Imperial Forest Research Institute, Dehradun, in 1906 and it is a premier institute under the Indian Council of Forestry Research and Education (ICFRE). The institute's history is virtually synonymous with the evolution and development of scientific forestry, not only in India but over the entire sub-continent [14]. The grand building spread over 450 hectares, styled in Greco-Roman and colonial architecture influences by C.G. Blomfield. The building is said to have been completed in seven years with a cost of about 90 lakhs at the time of construction [15].

The building was constructed completely as a single unit during the period of 1923 to 1929 and there was no addition to the building later. The building resembles Gothic Architecture similar to Edinburg University (UK) and several other buildings around the world. The FRI building is a masonry structure very well constructed with complete homogeneity throughout the structure with respect to material construction. It is a brick masonry building constructed in lime-sand mortar.

Experimental

Materials and methods

Mortar and brick samples were collected from different locations of the building. During sampling, care was taken to ensure that the original material does not go through any damage. Therefore, instead of the core drilling method, sampling with hand and help of hammer and chisel was preferred. The Sample location and details are given in Table 1.

The analyses work was carried out with a significant amount of the samples in order to avoid the errors. The obtained samples were subjected to physical, chemical and mechanical characterization for microstructural, mineralogical and compositional properties apart from their appearance, color and texture. Bulk density, water absorption and compressive strength of bricks were determined using standard test methods as per IS 3495 part I & II [16].

Table 1. Details of mortar and brick samples collected from different location

Sample code	Sample description	Location of the samples
FM1	Mortar	Main Building; Back side external wall
FM2	Mortar	Main Building; Back side Internal wall
FM3	Mortar	Main Building; corridor; external wall
FB1	Brick	Main building foundation block back side
FB2	Brick	Main building foundation block front side
FaB3	Brick	Main Building; Back side external wall: Facial Brick
FaB4	Brick	Main Building; Corridor; external wall: Facial Brick

Characterization of mortars and bricks

The petrological analysis was carried out to analyze the lime mortar samples under the polarized light microscope with Metavis image analyzer user-interactive software. For this, the sample was dried to evaporate any entrapped moisture. After those materials mounted on glass slides impregnation in low viscous epoxy resin under vacuum, a thin section slide was about 20-30μm so that light can easily pass through. X-ray fluorescence (Bruker WDXRF; model: S8

TIGER) was used for the chemical analysis of mortar and brick samples. The results were obtained in the form of major oxides. The mineralogical composition was analyzed using X Ray diffractometer (Make: Rigaku; model: DMax 2200) with the scanning steps 1°/min in a range of 5 to 80° diffraction angle using Copper (Cu Kα) as X-ray source with wavelength (λ) of 1.5406 nm.

The morphological studies of the lime mortar samples were carried out using Field Emission Scanning Electron Microscopy (make: TESCAN; model: MIRA 3). The samples were fixed into aluminum stub with the help of two-sided carbon tape and the gold coating was applied by using Sputter coater. The Energy Dispersive X-ray Spectroscopy (EDX Bruker X Flash 6I10) was used to find the semi-quantitative chemical composition of the mortar samples. Together, these techniques provide the fundamental composition information for a wide variety of materials. Thermal degradation of samples was observed using a Thermal analyzer (Make: Perkin Elmer, model: Diamond TG/DTA). Samples were taken in a ceramic pan and heated in a nitrogen atmosphere with the temperature range 20 to 1100°C with a controlled heating rate of 5°C/min. The functional group analysis was carried out using the Fourier Transformation Infrared FTIR (model: NEXUS (1100), Thermo Nicolet, USA) spectroscopy and the spectra were recorded in the region of 4000–500cm^{-1}

Results and discussion

Many of our ancient structures constructed with lime mortar and brickwork that exhibited superior durability as compared to modern structures based on cement/concrete. It was found that use of cement is incompatible with many ancient materials because of the presence of soluble salts such as calcium sulfates and sodium salts. These salts can leach out over time and can quickly damage the surrounding materials.

The repair and restoration of heritage structures are very much needed. For the restoration and repair work, it is crucial to understand the detailed chemical, mineral and structural composition of the already used materials in order to develop a compatible material.

In FRI building construction, two types of bricks have been used (Fig. 3) termed as foundation bricks and facing bricks which differ in their sizes. A total of four brick samples, two foundations and two facing brick have been collected from the different locations of the building (Table 1).

Fig. 3. Photograph showing building with foundation and facial bricks:
(a) Foundation brick (b) Facial brick (c) from FRI, Dehradun Building

Visual analysis of Building

The site visit of the building shows that lichen and algae affect the walls of the building (Fig. 4a). The activity of both organisms altered the appearance of the walls. Also, they have a corrosive effect on the substrate because they release acid metabolites. The use of cement has been found in many locations without testing their compatibility with the original materials which has created irreversible damage to the historical masonry. Indeed, cement-based mortar restrains movement and leads to stress that cause failure in the original masonry.

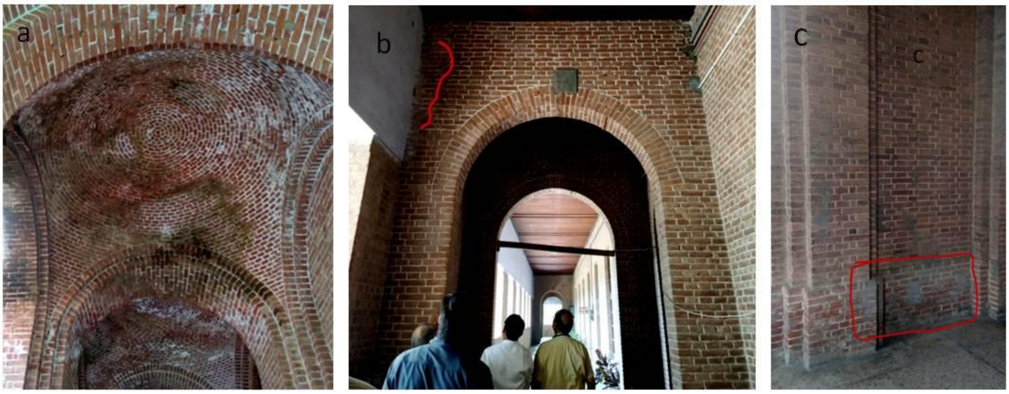


Fig. 4. Site inspection (a) algal attack on wall (b) crack on the arch wall (c) use of cement

Looking at the current state of building, it is quite clear that the repair attempts made have not been very successful or effective (Fig. 4b and c) and the original building materials are generally renewed without understanding their material characteristics and identification of their deterioration problems. This suggests that there is no comprehensive study undertaken so far on identifying the original materials used.

Analysis of Brick

Samples were collected from different locations of the buildings, as summarized in Table 1. Bricks are reddish-brown in color (Fig. 3) and were cleaned and air-dried for two weeks which was later on kept in an oven at 105 ± 2°C for 16 h, as specified in the IS 3495 part 2 [16].

Water absorption

To know the quality and strength of the clay bricks, water absorption is very useful measurement. The lower value of the water absorption is always desired for a good quality of the clay bricks. For the water absorption test, all bricks were dried in an oven at 100-115°C, and dry weight was measured, after which bricks were saturated overnight in water and weighed again.

The water absorption was found in the range of 10.9 to 18.5% (Table 2).

Table 2. Test results of brick samples

Sample name	Size (mm) (LXBXH)	Water absorption (%)	Porosity (%)	Bulk Density(g/cm^3)	Compressive strength (MPa)
FB1	225 ×110 ×64	11.0	16.2	1.94	13.8
FB2	222 × 110 ×65	10.9	15.5	1.96	14.2
FaB3	212 × 103 ×38	18.0	31.5	1.71	8.5
FaB4	212 × 103 ×37	18.5	32.2	1.66	7.8

FB; Foundation brick, FaB; Facial brick

The water-absorption is mainly depending on the pore size and their distribution in the bricks. It is generally due to the presence of high amounts of clay minerals generally silica, alumina and iron content in the composition of raw material [17, 18]. The acceptable water absorption limit for clay bricks is less than 20 percent. When bricks are highly porous, then there are high chances to absorb the moisture from the mortar (particularly in warm weather), which may cause damage to the brick. The porosity (Table 2) of the brick samples is found to decrease with decreasing the water absorption and all the analyzed brick samples show the apparent porosity in the range of 15.5-32.2 percent.

Compressive strength

The mechanical properties of the brick samples were determined by uniaxial compressive strength [16]. The test was carried out on the bricks which were perfect and free from cracks. Care was taken to have parallel upper and lower surfaces. The results obtained reveal that the compressive strength of all four brick samples was in the range of 7.8 to 14.2MPa (Table 2), which indicates the excellent quality of the bricks. It is generally considered that the clay brick samples having low water absorption and porosity have high bulk density and expected high mechanical strength also [19].

XRF analysis of brick

It is imperative to know the exact chemical and mineralogical composition of the original brick's samples so that new specific bricks with almost similar specifications and raw materials can be formulated. To know the chemical composition of all four bricks (FB1-FaB4), the X-ray fluorescence (XRF) analysis has been carried out and the results are given in Table 3.

Table 3. Chemical composition of brick samples

Oxides (%)	FB1	FB2	FaB3	FaB4
SiO_2	71.7	73.0	69.5	70.7
CaO	4.0	3.8	2.9	3.2
Al_2O_3	7.6	6.2	6.3	6.8
MgO	3.3	2.9	1.9	2.1
Fe_2O_3	8.7	9.6	8.4	8.5
K_2O	4.2	4.5	4.3	4.0
P_2O_5	1.1	1.4	1.2	1.3

The analysis of bricks samples revealed that all four bricks are similar within each provenance having SiO_2, as the main oxide component. It also confirmed that the same raw material had been used for the manufacturing of both types of brick.

The relatively high amount of iron content in brick samples is responsible for the reddish - brown colour. Iron oxide works as a natural coloring agent for clay bricks, more the iron content darker the brick color [20]. The low content of calcium oxide (less than 6%) is indicative of the use of non-calcareous clays [21]. This favored the formation of plagioclase phase minerals in bricks when they get fired. The presence of sodium, potassium and oxides of magnesium and calcium make it possible that clay generates the vitreous phase at a higher temperature [22].

Mineralogical and Morphological analysis of brick

The mineralogical analysis of the brick sample showed that bricks were mainly composed of quartz, potassium feldspar, hematite and albite minerals (Fig. 5).

The quartz mineral in bricks prevents them from cracking and shrinkage problem and also provides them a uniform shape. The durability of bricks depends on the proper proportion of quartz in the original raw material [23]. The presence of potassium feldspar shows that alkali oxide combines with base elements of the bricks (SiO_2 and Al_2O_3) to form new mineral phases such as potassium feldspar and sodium feldspars [24]. The absence of diopside, anorthite and other calcium-containing clay minerals approach the use of non-calcareous clay for the manufacturing of bricks. The hematite peak is resulted from the presence of iron oxide and confirms that the firing temperature of the bricks was nearly 850°C [25].

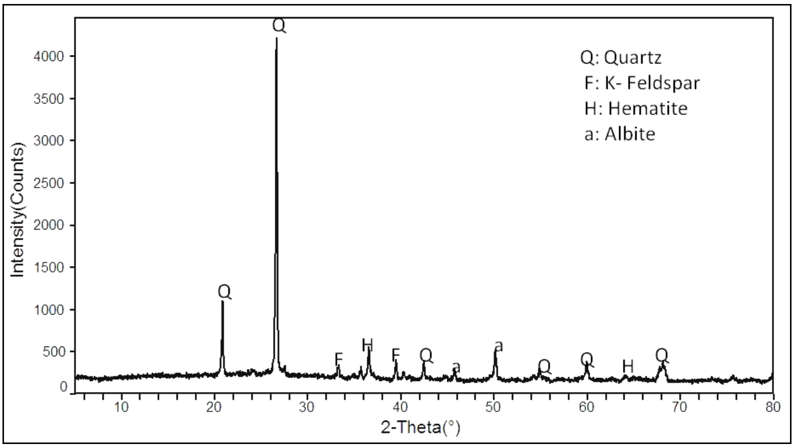


Fig. 5. XRD spectrum of brick sample No.FB1, FRI building

In addition, the invisibility of high temperatures peaks such as mullite and cristoballite in XRD analyses indicate that the firing temperature did not exceed 900◦C [26]. Based on the XRD results, it can be inferred that the bricks were manufactured at a temperature below 900°C. The SEM image of the B1 brick sample is shown in Figure 6. The gross elemental weight percentage composition of the brick sample was about 35% Si, 12% Al, 3% Fe, 2% K and Mg. The absence of a detectable limit of calcium by SEM-EDX analysis (Fig. 6) showed that raw material containing non-calcareous clay was used.

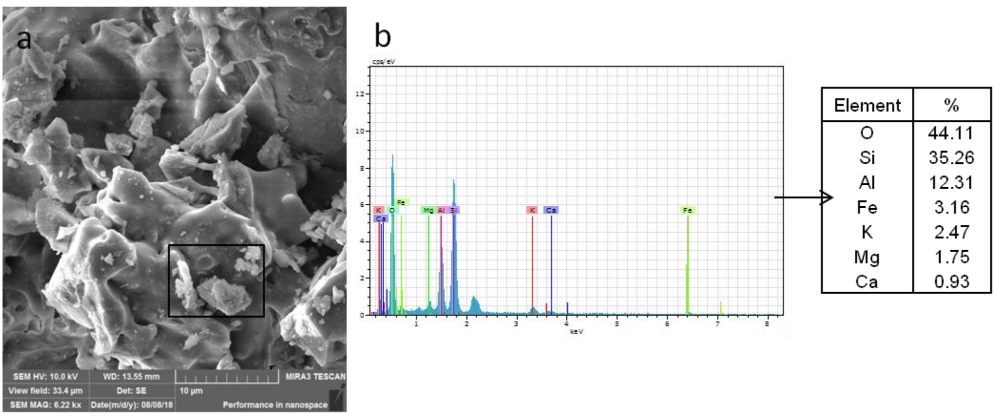


Fig. 6. FE-SEM micrograph (a) FB1 brick sample, (b) EDX spectrum along with elemental composition

The microstructure of the FB1 sample does not show any vitreous (Fig. 6) structure suggesting that bricks were not fired at high temperatures. XRD analysis results also supported this finding.

TGA analysis of Brick

The TGA analysis curve of FB1 brick shows three distinct weight losses around 80°C, 300–400°C and 400–520°C (Fig. 7). The first weight loss (0.67%) was due to loss of moisture content while the second weight loss of around 0.38% was due to hygroscopic water and the third weight loss of around 0.40% was due to the dehydroxylation. The percentage weight loss during TGA analysis was given in Table 4.

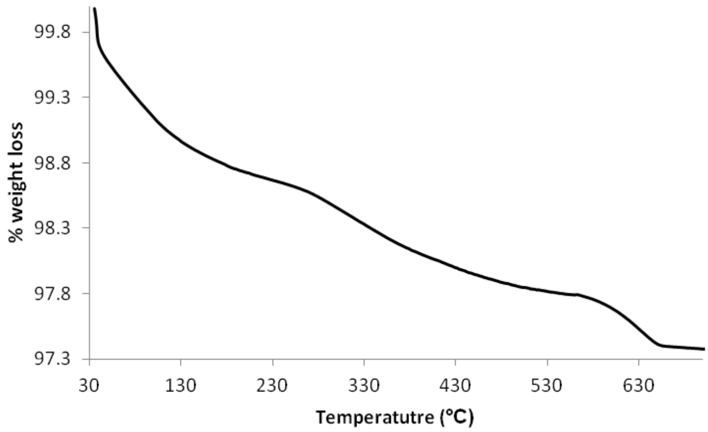


Fig. 7. TGA diagram FB1 Brick sample

Table 4. Thermal analysis of brick and mortar sample

Sample	Weight loss per temperature range (%)			
	< 120°C	**120 – 400°C**	**400 - 550°C**	**600 - 800°C**
FB1	0.97	0.93	0.28	0.32
FM1	1.71	3.52	3.04	12.71

Analysis of Mortar

Lime mortars, produced by mixing lime and aggregates (in the form of surkhi and brick dust), have been the most basic and common binding material (Fig. 8) used in the construction of so many buildings up to the discovery of cement [26]. The lime and aggregates stick to each other better, and the voids between the aggregates are filled with lime [27].

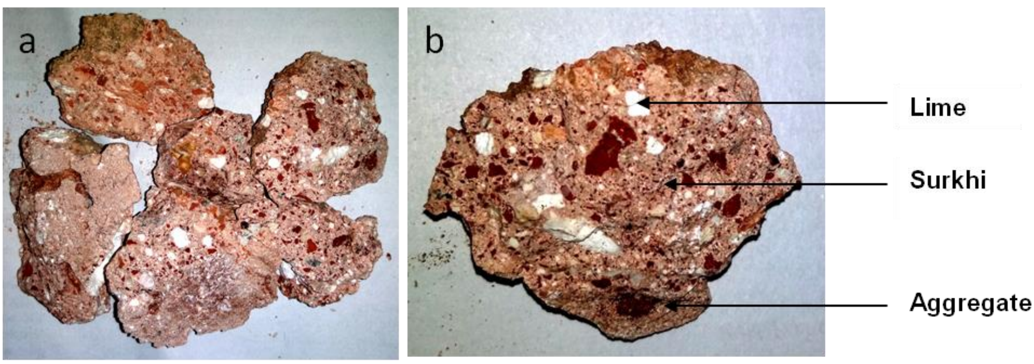


Fig. 8. Photograph (a) collected mortar samples
(b) FM1 sample indicating the presence of lime, surkhi and aggregate

In the present study, the characteristics of the mortars used in the FRI, Dehradun building has been determined in order to produce a similar mortar for future intervention. These mortars were mainly composed of calcium hydroxide and brick aggregates which generally converted into calcite through carbonation reaction. The binder/aggregate (B/Ag) ratio was around 1:2.5 by weight.

The samples were examined using the magnifying glass in order to get complete information about the color, texture and appearance of mortar. The examination revealed that samples were orange-pinkish color with hard, stiff and compact texture due to strong cohesion between brick aggregates and lime. In the FM1 sample (Fig. 8), rounded nodules of lime were clearly visible in white lumps form indicates that the lime was under/over burnt. All of these are presumably calcium carbonate, which in accordance with the XRD data.

Petrological analysis of mortar

The petrological thin section analysis of FM1 (Fig. 9a and b) mortar samples were carried out using a polarized light microscope.

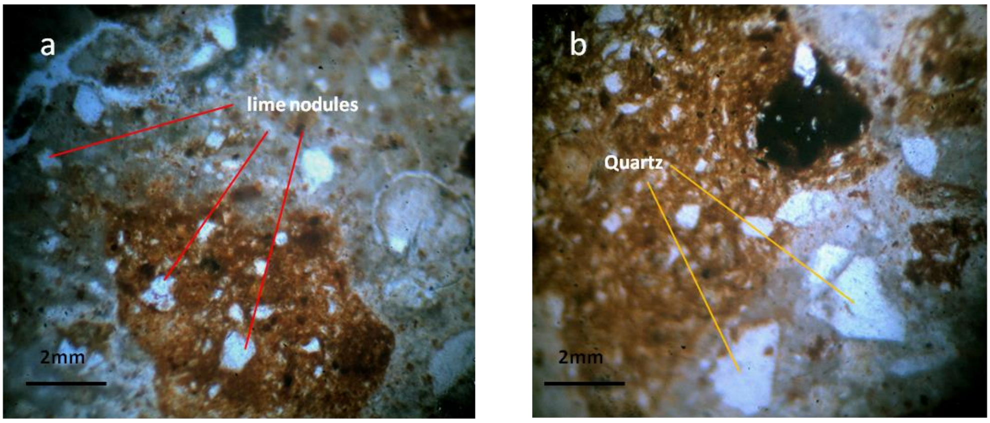


Fig. 9. Thin section image of lime mortar under a polarized light microscope at 100× magnification: (a) and (b) showing the presence of lime nodules and quartz in FM1 sample

The analysis of the FM1 mortar sample shows the presence of rounded nodules of lime, locally known as kankar, bajri and rori. These lime nodules are a very common characteristic of Indian ancient Indian mortar. Very fine-grained brick dust, together with medium to coarse-grained brick aggregates, were also present in the mortar matrix (Fig. 9a and b), and they were perfectly and firmly embedded with lime.

The mixing process, composition and size of aggregates also play a vital role in the mortar mix. When aggregates with medium to coarse size distribution and angular to the sub-angular inert filler of varied size embedded in the fine matrix of lime, then it provides excellent adhesion and improves the strength of mortar [28, 29]

XRF analysis of mortar

The chemical composition of mortar samples was tested using X-ray fluorescence spectrometry (XRF) analysis, and the elements present in our mortar samples were given in Table 5.

Table 5. Chemical composition of mortar samples

Sample	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	LOI
FM1	38.72	30.78	5.21	1.13	2.25	1.37	20.42
FM2	39.15	30.29	5.15	1.24	3.04	1.23	19.89
FM3	38.21	30.54	5.54	1.42	2.64	1.34	20.21
FM3	38.29	31.46	5.97	1.31	2.83	1.41	18.62

From the results, it was observed that silica and calcium oxide was the major component in all four mortar samples. The content of the oxides was determined as follows: CaO 30-31%, SiO_2 38-39%, Al_2O_3 5-6%, MgO 2-3% and K_2O 1-1.4%. The presence of the high amount of silica and alumina in mortar samples may be the interference of the aggregate portion which was added in the form of surkhi and brick dust.

Mineralogical and morphological analysis of mortar

The XRD analysis of FM1 mortar samples shows that they were mainly composed of calcite and quartz (Fig. 10a and b). The calcite phase predominating in the XRD pattern comes from carbonated lime, and peaks for siliceous minerals visible in XRD originate from aggregates.

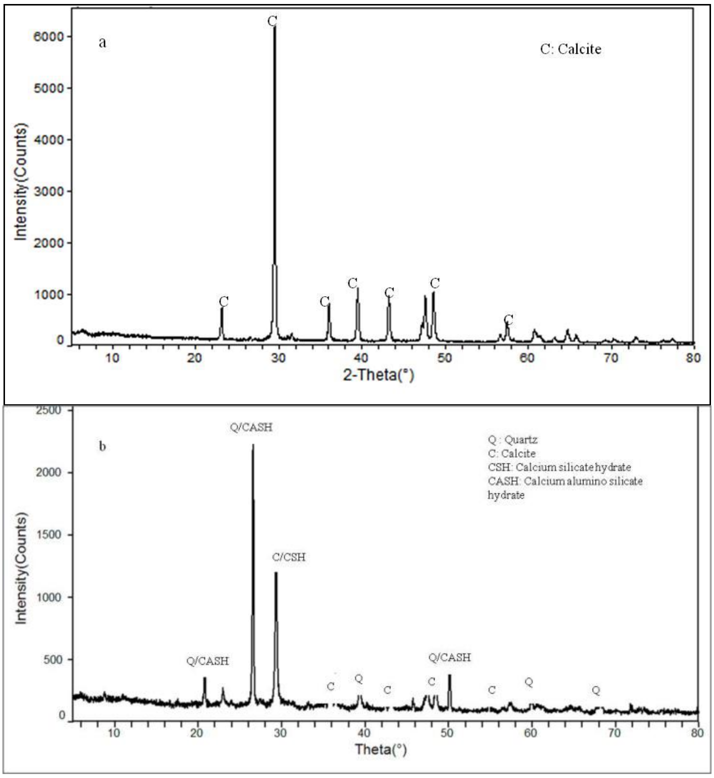


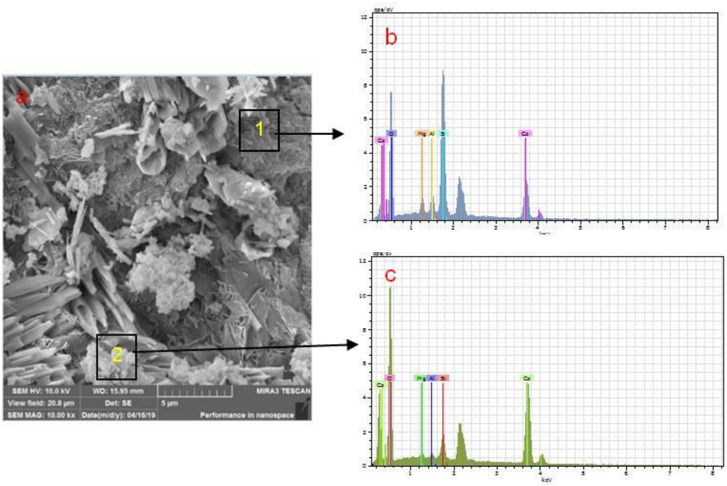
Fig. 10. XRD spectrum of (a) 'white lump' part FM1 sample (b) FM1 mortar sample

If silicate phases, in particular, clay minerals and quartz, are present additionally, then hydraulic or latent hydraulic/pozzolanic components may form during the firing of the limestone, provided that temperatures are sufficiently high in contact with water, they will hydrate to form calcium silicate hydrate phases. The silicate phases provide strength to the mortar matrix [30].

Peaks for hydraulic reaction products of C-S-H in FM1 mortar sample are coincide with the main calcite peaks. The morphological studies of FM1 samples were carried out using FE-SEM and result obtained shown in the form of Figure 11a and b. The area 1 of FM1 mortar sample indicates the presence of calcium silicate complex and area 2, confirms the presence of calcite as confirmed from the semi-quantitative EDX analysis (Fig. 11a and b).

Binder aggregate ratio

The B/Ag ratio is an important parameter influencing the physical, mechanical, and durability of mortar. The amount of lime and aggregates should be accurate so that the mortar with excellent workability, durability and strength was produced [30]. The composition of the mortar mix was determined after the dissolution of the mortar sample in dilute HCl which separates the aggregates in-to the insoluble form and binder (calcium content) including clay minerals in soluble fraction. The calculated B/Ag ratio for FRI mortar was 1:2.5. The B/Ag ratio in some ancient buildings was also reported in the range of 1:1 to 1:3 although, the amount of binder was increased in the lime plaster [31]. In the 1:3 mortar mix, the aggregate content is high and in 1:2, the lime content is high therefore, the existence of free lime or unreacted lime was present in the later one. According to Moropoulou, the 1:1-3 mortar mixes are used in the places where a drastic change in atmospheric conditions is not occurring. This range of ratio provides appropriate strength, durability and workability to the structure, and this may be one of the reasons for the existence of ancient monuments and structures without any significant deterioration [31].



Element	Area1
O	59.8
Si	22.2
Ca	13.6
Al	2.2
Mg	1.9

Element	Area2
O	74.2
Si	2.9
Ca	21.9
Al	0.3
Mg	0.45

Fig. 11. FE-SEM micrograph (a) FM1 mortar sample and EDX analysis along with their chemical composition (b) area 1 (c) area 2

The composition and hydraulicity of the binder have an important effect on the properties of the mortar and it can be quantified with wet chemical methods [32]. Hydraulicity (HI) and Cementation indices (CI) of lime can be calculated as per Boynton (1) and Vicat Eqs. (2), respectively [33, 34]:

$$\text{Hydraulicity index (HI)} = \frac{(\%Al_2O_3 + \%Fe_2O_3 + \%SiO_2)}{(\%CaO + \%MgO)} \quad (1)$$

$$\text{Cementation index (CI)} = \frac{(2.8\,SiO_2 + 1.1Al_2O_3 + 0.7Fe_2O_3)}{(CaO + 1.4\,MgO)} \quad (2)$$

The calculated Hydraulicity and Cementation indices for mortar samples are 0.2 and 0.5. The indices values are directly proportional to the hydraulic property of mortar higher the index value, more the hydraulic nature of the mortar [35].

TGA and FTIR analysis of mortar

TGA analysis was generally used to identify the mineral component and reactions associated with mortar/ plaster under the control heating environment. The Thermal analysis curve of the FM1 and mortar sample is shown in figure 12. From TGA graph, it can be seen that there was a continuous weight loss of about 1.13% at 120°C, which shows the presence of adsorbed water and the weight loss of about 0.5% around 120 - 240°C was due to the hygroscopic and internally bonded water molecules with calcium and magnesium silicates.

The 2.2% weight loss between 300-500°C was probably due to the breakdown of the calcium and magnesium hydroxide molecule. Most of the weight loss around 12.33% appears in the range 600–800°C, indicating the decomposition of carbonates [36] as shown in Table 5. Hydraulic properties of the mortar sample can also be evaluated by determining the percentage of weight loss due to chemically bound water (200-600°C) and due to the decomposition of carbonates (over 600°C) [37, 38]. It has been reported that in a given mortar, if the ratio of CO_2/H_2O is between 1 and 10, then it can be accepted as a hydraulic lime mortar [39]. In FM1 mortar, the ratio of CO_2/H_2O is 1.04. Hence, TGA analysis of mortar samples confirmed the hydraulic nature of the mortar and results are correlated with wet chemical analysis.

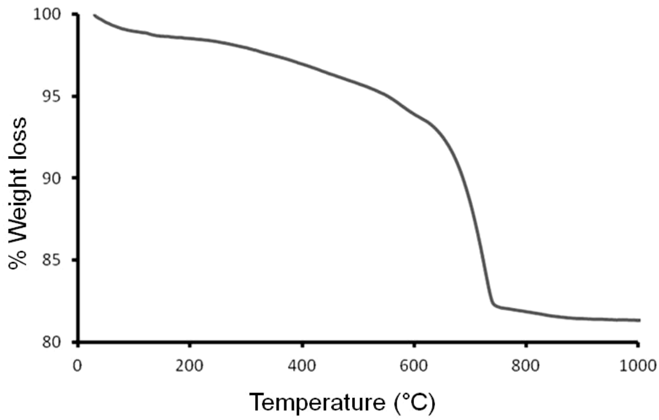


Fig. 12. TGA diagram FM1 mortar sample

The FTIR spectra of FM1-FM3 mortar samples are shown in figure 13.

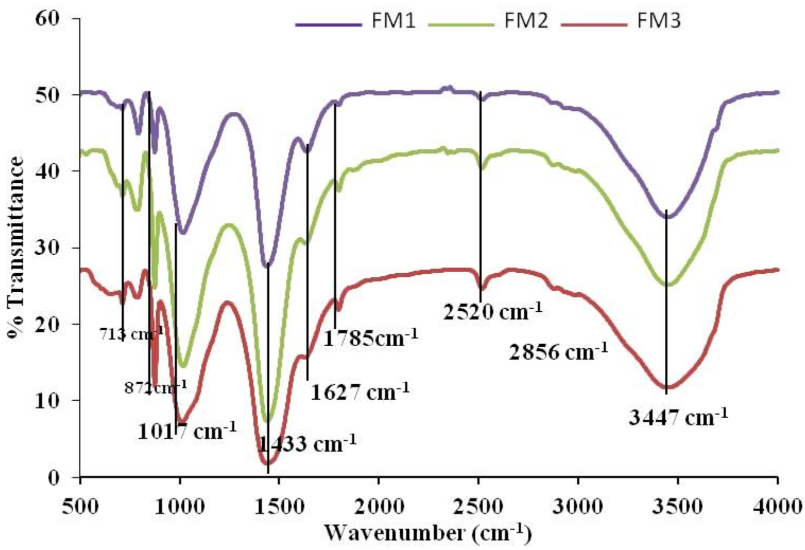


Fig. 13. FTIR spectra of lime mortar samples

FTIR spectra of all three samples are identical, containing the same absorption peaks. It can be seen in figure 13 that all three samples displayed a broad stretching intense characteristic peak near 3430cm^{-1} due to hydroxyl stretching vibration of the polysaccharide fractions, and a weak C–H stretching vibration band in the region of 2856 and 2520 cm^{-1}. The band towards 1750 cm^{-1} (1785 and 1627cm^{-1}) was attributed to the stretching vibration of C=O. Peak recorded in the region of 1017 and 470cm^{-1} shows the presence of Si-O bond containing plane as well as out of plane bending and stretching frequency. The characteristic peaks of calcite present at 713, 872 and 1433cm^{-1} [40].

Previous studies suggest that in ancient lime mortar and plasters different admixture were used to enhance the setting properties of mortar and also for improving workability, strength and carbonation process [41, 42]. In ancient times these admixtures were incorporated with building material and worked like air-entraining agents that help in improving the adhesiveness and water-retaining properties [43-45]. Although it is notoriously tricky in full identification of organics using FTIR analysis so, further qualitative tests should be performed to confirm these assumptions.

Conclusions

Various Physico-chemical and analytical methods have been used to analyze the composition of mortar and brickwork of FRI, Dehradun building following conclusions can be made:

a. In order to replace the broken/deteriorated bricks, new bricks using locally available clay in the size of 225×110×65mm for foundation and 212×103×38mm for facial bricks can be manufactured by firing below 900°C in traditional brick kilns so as to ensure the size, shape, colour, and compatibility with the original bricks.

b. The analysis of mortar samples shows that lime, surkhi, and brick aggregates are commonly used in the preparation of mortar samples which were very common practice during that time and has been used to improve the fractural and durability properties of mortar.

c. The addition of brick aggregates and surkhi with lime binder cause pozzolanic reaction at the brick lime matrix and the pores of the bricks these products provide strong adhesion bond to make mortar more durable and stiffer.

d. The FTIR result indicating the use of organic admixture in the mortar mix. Various investigations revealed useful information about the lime mortar and brickwork used in the historic structure.

As these structures require conservation from time to time, therefore, in order to use compatible material for restoration work, suitable strategies in regard to material development may be adopted. This study will be useful to prepare mortar and bricks of high compatibility for future restoration work.

Design of repair mortar and Brick

From the evaluation of the results, it was concluded that the mortars samples were made from the same type of raw materials (binders, aggregates). In order to proceed to design of repair materials traditional binders, such as hydrated lime, natural pozzolan, fine sand, as well as natural aggregates can be use. Natural pozzolan with small to medium size can be added in mortar mix which can contribute to the strength development. Further, larger size of broken brick aggregate having low surface area may not contribute to the pozzolanic reaction with the lime The brick dust shall be added for the color match it can also contribute to the pozzolanic reaction. The B/A ratio of repair mortar should be 1:2.5 by weight. Mortar selection is best based on water retention capability, trowel-ability (flow) and shrinkage; lime-surkhi is very suitable in this regard. Failures hardly occurs at bond, but deterioration of mortar and brick at the joint (e.g. leached sulfate of brick may attack cement mortar) may result in de-bonding. Weakness in masonry is due to incompatibility in elastic modulus and Poisson's ratio of brick and mortar. So it is very important to match the compatibility of repair mortar with existing bricks.

In this regard the physico-chemical analysis of bricks has been also carried and results shows that existing bricks have low water absorption as well as porosity and high bulk density which are responsible for their high compressive strength and vice versa.

The collected brick samples were found to have two types of dimensions due to their use the one brick is thinner (dimensions 212×103×38) used as facial bricks while the thicker one (dimensions 225×110×64) is used as foundation brick. The chemical composition obtained from XRF analysis clearly depicted that both bricks were composed of high amounts of SiO_2, Al_2O_3, Fe_2O_3 and considerably low amounts of K_2O, MgO and CaO. The scanning electron microscopy with EDX also confirmed the XRD results for using the Ca-poor clays for the brick manufacturing. The estimated temperature range of 800-900ºC based on minerals transformation and microstructure studies.

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