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Assessment of Climate Change Impact, Resistant Behavior, and Adaptation Possibilities on 16th to 18th Century CE Mughal Period's Brick Monumental Structures of Haryana Region of the Indian Subcontinent

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ABSTRACT

The value of the monumental structures of the Mughal era (1526 CE-1761 CE) of the Haryana region of India lies not only in its role as a witness to the rise and fall of the Mughal and Colonial eras, but also because it provides physical evidence for the austere tradition of give and take comprising the living knowledge and skill of Islamic architecture and indigenous skills, along with the geological origin of raw materials, artificial manufacturing, longevity, and durability of these huge earth-based masonry structures. Unfortunately, alterations due to the vagaries of weather and climate have badly affected the monumental structures, with even more damage possible in the future. Therefore, the objective of this work is the assessment of these monumental structures in terms of conservation and restoration work. Their survival thus far has been due to differences between the past and present climatic conditions, the structural strength of the monuments as a whole, and the durable characteristics of masonry materials. Hence, the identification of the environment affecting the monuments, and the intrinsic nature of masonry materials are valuable for determination of the expected stability and durability, and adaptation possibilities of monumental structures. Deterioration can be minimized by creating and retaining resilient environments around the monuments, which involves different approaches to planning, design, operation, management, value, and governance, and the use of suitable masonry materials as an adaptive measure, along with continuous monitoring of the actual impact.

Keywords: Mughal, deterioration, climate impact, durability, adaptation

INTRODUCTION

The reason why certain historic buildings and monuments have survived for such long periods is the difference between the past and present climatic conditions, and to some extent of the physical and mineralogical properties of masonry materials (Ward-Harvey, 2008). That is, due to ongoing and more frequent severe weather events, increased exposure, aging of materials, and the existence of previous conservation interventions, the need for adapting cultural heritage to anthropic and climate change related effects is becoming increasingly urgent. The risk from climate change is more pronounced for the built environment, where the right adaptation interventions should be chosen properly considering the buildings' capacity to change (Bertolin, 2019; Mani et al., 2018).

The climate can be defined as the entirety of atmospheric events such as rainfall, temperature, wind, and humidity that cause certain damage to monumental buildings over time (Yaldiz, 2010), while the physical and mineralogical properties of construction materials determine the resistance capacity of monuments toward damage caused by climatic factors (Siegesmund et al., 2002). For monumental structures, traditional building materials that have been used for their construction over thousands of years not only deliver structural strength, but to also withstand weathering (Francis & Buras, 2019).

Climate fluctuations cause deterioration of historic buildings and monuments, including aesthetic, physical, chemical, and biodeterioration, which affect the surroundings, such the soil and foundation, and cause other problems (Bonazza et al., 2009) depending on regional climate change or other weather agents, i.e., temperature, water (relative humidity), the power of wind, etc. The direct impact on cultural heritage and monuments is usually focused on such aspects as specific damage and erasure, while indirect impacts often involve issues such as changes in groundwater level or dangers from vibration (Jerpåsen & Larsen, 2011).

In monumental structures, the damaging effects of extreme climatic changes and weather are obvious, but the constant damage caused by everyday conditions has a cumulative and synergistic effect (Koestler et al., 1994). These conditions include temperature and humidity cycles (Flatt, 2002; Palomo et al., 2002), alternating condensation and evaporation (Charola, 2000), salt dissolution and re-crystallization (Genkinger & Putnis, 2007; Scherer, 2004), transformation of minerals (Bauluz et al., 2004), and favorable conditions for growth of biological life (Gaylarde et al., 2003), etc. In addition to these natural factors, the present-day unchecked levels of development, which lead to industrial pollution (Belfiore et al., 2013; Rampazzi et al., 2011), economical/industrial development (Dayal et al., 2010), etc. exert catastrophic effects on these structures; eventually, these anthropogenic factors are more destructive.

The Mughal ruled over the Indian subcontinent for more than 300 years and built many magnificent monumental structures as the sum of the social, economic, political, and cultural developments of their reign (Malik, 2008). The period of the effervescence of the Mughal rule in India (1526 CE-1761 CE), was very eventful both politically and culturally with respect to the establishment of a new regime, and in the austere tradition of give and take of the living knowledge and indigenous skills of masonry materials (Chandra, 2003; Grover, 1981). The Mughals brought changes in architecture and manufacturing technologies of masonry materials (e.g., brick, stone, lime, etc.) used in monuments of the Indian subcontinent (Gajrani, 2004).

The monuments of Haryana provide physical evidence for the geological origin, artificial manufacturing, longevity, and durability of the huge masonry structures in this aggressive environment. Unfortunately, monuments of this region have suffered badly, not only due to the vagaries of time and associated factors that comprise the phenomenon of 'natural aging' and extensive vandalism, but also due to natural and anthropogenic environmental factors. They are now at a critical stage. So, this work assesses these parameters of rainfall, temperature, wind, salt action, bio-deterioration etc., on four brick Mughal era monuments of the Haryana region in order to establish a baseline conclusion regarding preventive conservation and protection of similar monuments.

MATERIALS AND METHODS

Study Area

The studied monumental structures (Figure 1) are huge masonry structures of fired-clay bricks that were selected due to their historical importance, architecture features, construction techniques, masonry materials and surrounding environmental parameters (Table 1). These monumental structures not only provide evidence of glorious history, architecture, longevity, durability but also provide evidence of changes in the climatic scenario of the region, which comprises the research framework of this particular study (Figure 2). The region is surrounded by natural geographical boundaries of rivers (Yamuna in the east, Ghaggar in the west) and hills (Shivalik in the north, Aravalli in southwest). The overall climate of the study area is subtropical, semi-arid to sub-humid, continental, and monsoon type; it is mainly dry with a scalding summer (30 °C - 48 °C) and cold winter (5 °C - 25 °C) except during the monsoon season when moist air of oceanic origin penetrates in the state. The annual rainfall of the region is 560 mm.

The population of the state has increased by 19.90 % at a time when the nation overall has experienced an increase of 21.34 % (Census of India, 2011). The industrial and vehicular population has also increased several times during the last five decades (Department of Economic and Statistical Affaire, 2019a; Department of Economic and Statistical Affaire, 2019b). This high rate of growth and constant socioeconomic development have put pressure on natural resources and caused environmental and climate degradation in the region.

Figure 1

Mughal Period's Brick Monumental Structures of Haryana Region, India

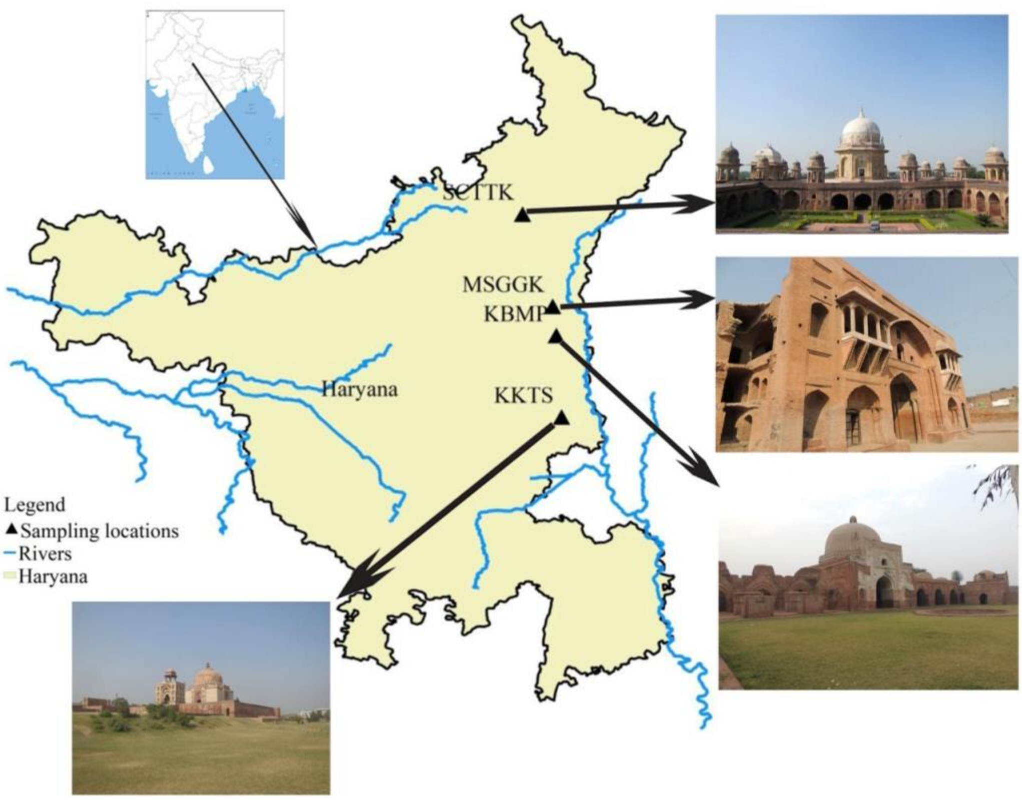


Table 1

Brief description of Mughal monumental structures of Haryana region, India

S.No.	Name of Study Sites	Code for Study	Geological Coordinates	Year of Construction	Characteristic feathers
1	Sheikh Chilli's Tomb, Thanesar, (Kurukshetra)	SCTTK	29°58.598'N, 76°49.688'E	CE 1650	Structure of Indo-Islamic architecture, ranked second only to the Taj Mahal in Northern India due to its unique and highly sophisticated architectural value. The masonry units are red color lakhauri brick with lime-surkhi mortar and cladded with red sandstone and marble.
2	Mughal Sarai Gateway, Gharaunda, (Karnal)	MSGGK	29°32.155'N, 76°58.307'E	CE 1637	Structure of Indo-Islamic architecture and masonry units are yellowish red color lakhauri brick with lime-surkhi mortar.
3	Kabuli Bagh Mosque, (Panipat)	KBMP	29°23.762'N, 76^{0}59.362'E	CE 1526	The first Mughal monument in India having Indo-Islamic architecture and masonry units is red and yellowish red color lakhauri brick with lime-surkhi mortar.
4	Khwaza Khizr's Tomb, (Sonepat)	KKTS	29°00.407'N, 77°01.337'E	CE 1522-24	Structure of Indo-Islamic architecture and masonry units are red and yellowish red color lakhauri brick with lime-surkhi mortar and cladded with kankar and red sandstone.

Rainwater Sampling and Analysis

Rainfall as a natural agent is responsible for scavenging of the atmosphere, and collects all types of components (natural and anthropogenic) that are suspended in the air. In order to evaluate the environmental envelope around the monumental structures, the physico-chemical status of the rainwater was determined. To analyze the physico-chemical status of rainwater, samples of rainwater (n=5) were collected from the roof top of each monumental structure using an in-house fabricated rainwater collector during the monsoon months from 2016 to 2018. The monsoon months were chosen because it represents the annual peak rainfall with respect to amount and frequency. After each collection, the pH values were measured with a digital pH meter (Systronics 361), and electrical conductivity was measured (EC, μS/cm) with a digital conductivity meter (Systronics 306). The concentration values of major anions (SO_4^{-2}, NO_3^-, Cl^-, and F^-) and cations (Ca^{+2}, Mg^{+2}, K^+, NH_4^+, and Na^+) were analyzed by 930 compact IC Flex ion Chromatograph, while concentration of bicarbonate (HCO_3^-) was determined using the acid titration method (American Public Health Association [APHA], 1995). The obtained concentration values (mg/l) of ionic species were converted in to μeq/l with the help of this equation:

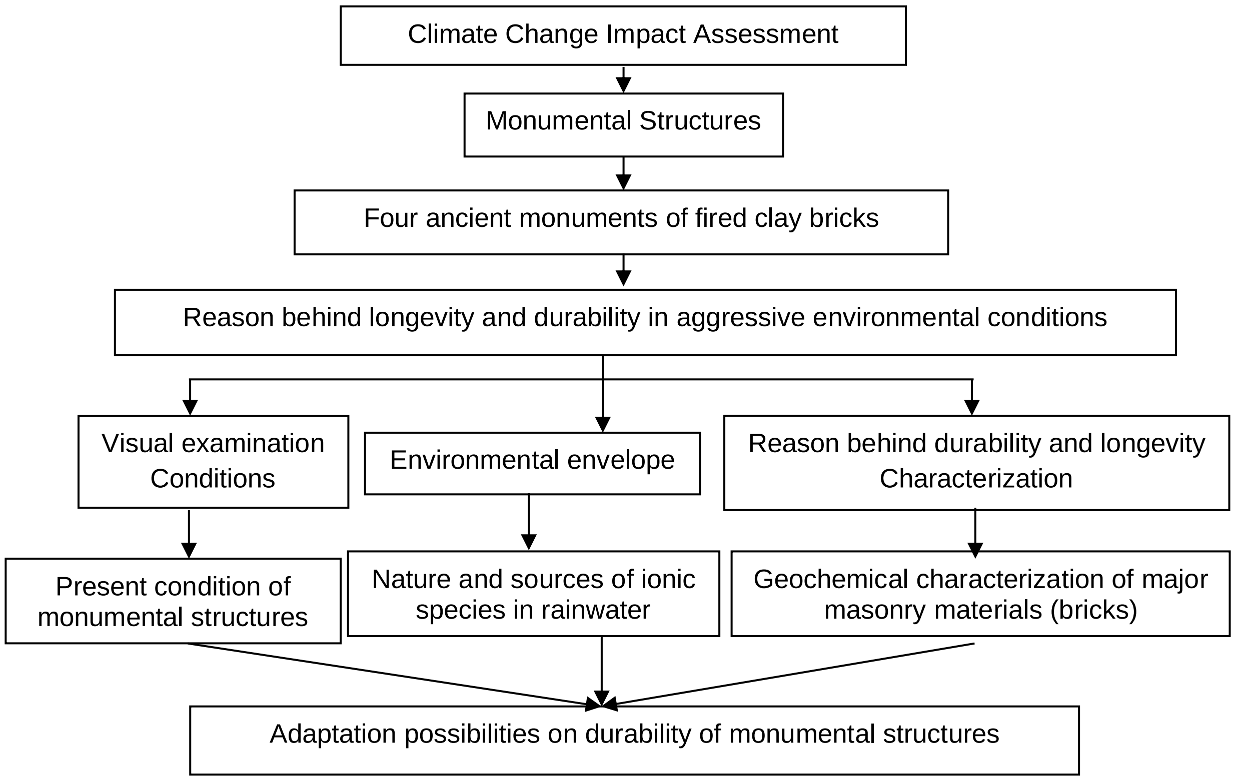
μeq/l = [(mg/l x Valence x1000) / Weight]

Brick Sampling and Analysis

The intrinsic properties of construction materials influence the resistance capacity of the built surfaces. To examine the reasons behind the survival of monumental structures in terms of construction materials (bricks), representative samples of brick (n=3) were collected from each monument in order to characterize their physical and mineralogical behavior. Given that the aim of the study and the conservation ethics demand that intervention should be kept to a minimum, samples (bricks) were collected by dividing each sample into three imaginary sections, and then drawing one sample from each section (Bureau of Indian Standards [BIS], 1978). The collected samples were visually examined, and then were cut into smaller briquettes of the same size (5.0 cm × 4.0 cm × 2.5 cm) for the characterization of physical behavior through the use of standard test methods (American Society for Testing and Materials [ASTM], 1997; American Society for Testing and Materials [ASTM], 2013; American Society for Testing and Materials [ASTM], 2016; Bureau of Indian Standards [BIS], 2007; Bureau of Indian Standards [BIS], 1992a; Bureau of Indian Standards [BIS], 1992b). For assessment of mineralogical behavior, brick samples were

Figure 2

Diagram of methodology



finely ground using an agate mortar, and then passed through a 300 mesh screen (53 micron-sized opening). Elemental compositions were identified from powdered brick samples through a boric acid pellet technique using PANalytical Epsilon 5-X-ray fluorescence. The mineralogical compositions were determined by PANalytical X'pert PRO-X-ray diffraction, and the validation of identified minerals was carried out through data file, Joint Committee on Powder Diffraction Standards (JCPDS) 1994. The molecular and mineralogical phases were identified by Perkin Elmer Spectrum 1-Fourier transform infrared spectroscopy (FTIR) analysis (4000 cm^{-1} - 450 cm^{-1}) through the KBr pellet technique.

RESULTS AND DISCUSSION

Visual Examination

During the on-site visual examination, accrued effects of three main weathering agents (rainwater/humidity, temperature, and wind) were identified that had contributed to the direct and indirect impacts on the monumental structures. It is observed that with respect to the deterioration of the monuments of this study, the most important factor is any form of water; in fact, it is the root cause of the deterioration. The condition of the monuments observed in this field survey attests that water, temperature, humidity, and wind promote other deterioration problems in the monuments, in addition to the human induced impact. The main deterioration patterns identified during the study of the selected monuments are given in Table 2; they show moderate to severe deterioration. Due to the accumulative effects of these problems, the surface masonry of these monuments has become roughened, and is affected by pits, pores, cracks, crevices, erosion, exfoliation, granular disintegration (Figure 3A, 3F: SCTTK), growth of vascular and non- vascular plant systems (Figure 3B, 3C, 3H: SCTTK, 3C: KBMP), missing parts (Figure 3B: SCTTK, 3G: MSGGK), the efflorescence of salt, dampness (Figure 3D: SCTTK, 3E: KKTS), and bulging and crumbling of materials. The roughened and pitted surfaces attract dust and pollutants, which are first deposited, and then react with the constituents of the materials to form a black crust, the layers of which acts as environment and climate change markers of these monuments, and reflect changes in micro-environments prevailing near the monuments (Perez-Monserrat et al., 2016).

Table 2

Identified deterioration patterns in the monumental structures of Haryana region, India

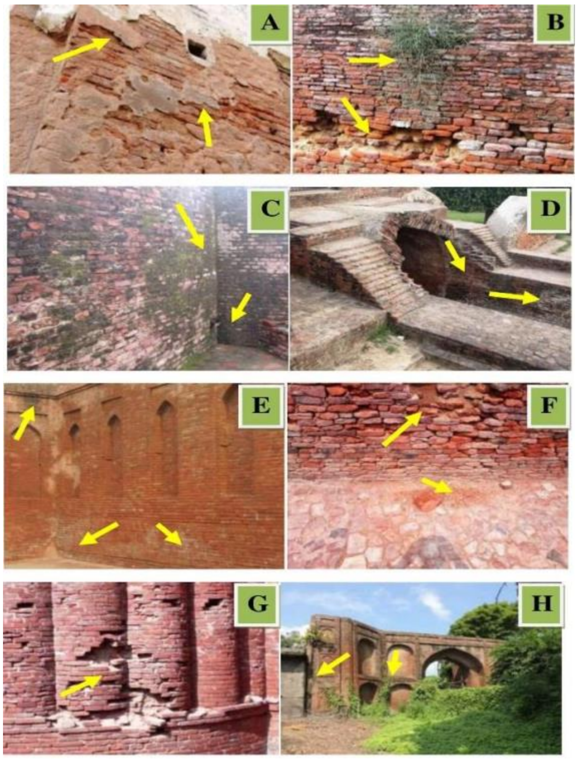
Factor (s)	**Deterioration Pattern**	**Observation**
Water and Temperature	Granular Disintegration Pulverization Powdering Crumbling Erosion	Damage caused due to rainwater, wetting- drying cycles, promotes loss of cohesion of masonry binding materials.
	Wide/fine cracks Splitting	Loss of cohesion of binding materials, promotes cracks and opening of joints.
	Pitting	Damage caused due to surface erosion and action of pollutants with dust particles, manifested in the form of large holes.

Table 2 (Continued)

Factor (s)	Deterioration Pattern	Observation
Salt in combination with water	Efflorescence	White patches on the surface of the masonry, due to crystallization and transport of salts.
	Flaking Blistering Scaling	Crystallization and transport of salts causes swelling below the exposed surface.
	Fading Staning	Discharge of water along with other ionic species (nutrients) forms stains which promotes the growth of other microorganism.
Moisture in combination with ionic species (nutrients) and temperature	Biocolonization	Biodeterioration and Biodegradation takes place due to dampness attracts pollutants, dust particles, and promotes growth of other microorganism.
	Vascular and non-vascular plant system	Micro flora provides nutrients and deteriorated surface, serves as the receptacle for growth, leads to further damage.

Figure 3

Identified Deterioration Patterns along with Growth of Vascular and Non-Vascular Plant Systems



Note. Deterioration: roughening (A & F), pits (A), pores (A), cracks (C & H), crevices (C & H), erosion (F), exfoliation (A), granular disintegration (A & F), missing parts (B & G), efflorescence of salt (D & E), dampness (C & E)

Past and Future environmental scenarios

The rainwater and temperature data of the Haryana region for the period from 1976 to 2018 (42 years) that is shown in Figure 4 (National action plan on climate change [NAPCC], 2008) indicates that the pre-monsoon and the monsoon seasons are increasingly warmer, and are consistent with national and global temperature scenario (Bhutiyani et al., 2007). The trend of increasing rainfall during monsoons combined with rising temperatures of pre-monsoon and monsoon seasons, comprise a major cause of climate change of the study area that affects the micro-environment of the monuments. Here, wind velocity and direction play an additional role in spatial and seasonal variations of these weather agents, as do pollutants (Gupta & Cheong, 2006). The impact of regional climate on projected climate change of Haryana region shows a considerable change in mean values of annual rainfall, and maximum and minimum temperatures (Figure 5) (NAPCC 2008). The projected mean annual rainfall shows an expected decrease of about 3 % by mid-century (2050), followed by an increase of about 17 % by the end of the century, while the monsoon months show marginal increases by mid-century, and a 14% increase by the end of the century. The projected mean maximum temperature is expected to increase by about 1.3 °C by mid-century, and 4.2 °C by the end of the century, while the projected mean minimum temperature is projected to increase by about 2.1 °C by mid-century, and 4.7 °C by the end of the century.

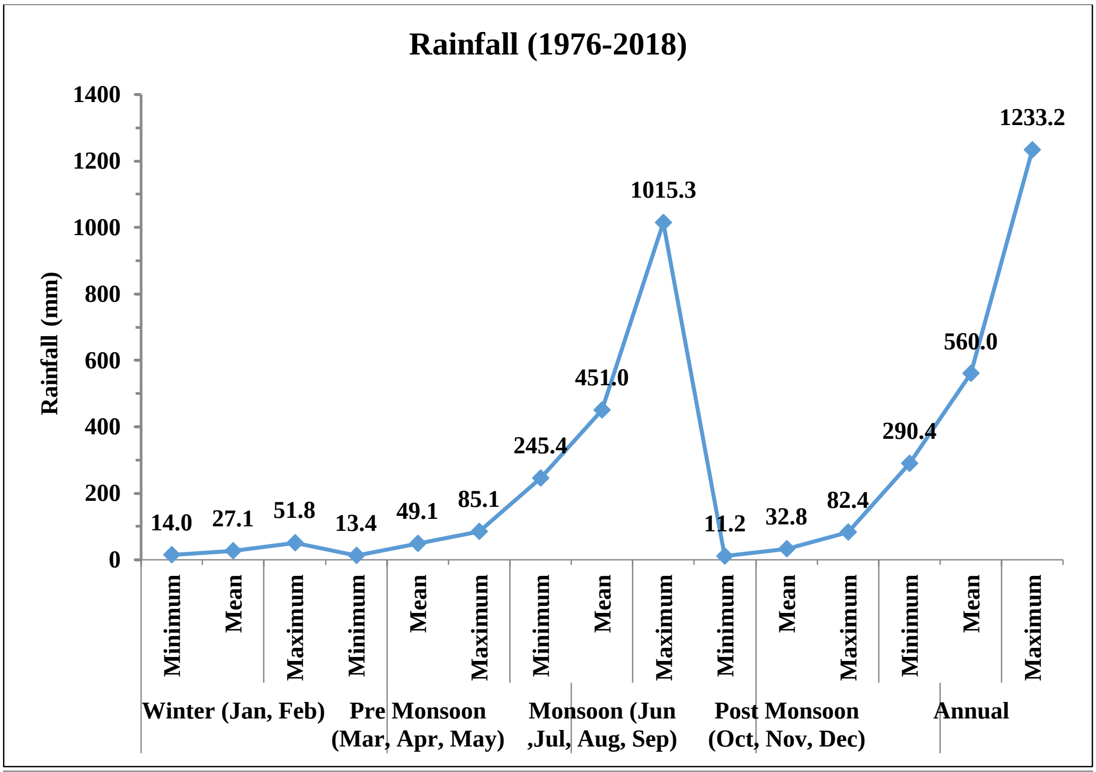
Present environmental envelope of the monuments

The monumental structures of this study are open to the elements, so it is critical to observe how the rainwater contacts the surface (i.e., a short drizzle or shower supply) and dynamic regime (i.e., laminar or turbulent) of the water flowing over the surface of the monument (Camuffo, 1986; Gong et al., 2011). The bricks of the monumental structures have small and large fissures, cracks, and pores into which the wind forces rainwater penetration, and from which repeated striking of raindrops detaches loose particles, all of which determines the moisture content in the bricks and accelerates the deterioration. In addition to the mechanical action conducted by rainfall, the characteristics of rainwater also contribute to the impact.

The mean values of three consecutive years (2016-2018) of rainwater pH, EC (μS/cm), and dissolved ions (μeq/l) around the monumental structures of the Haryana region are given in Table 3. The mean pH value (6.0) of the study sites shows that the monuments are in acidic environments, while higher EC is shown by KBMP (65.2 μS/cm), and lower by SCTTK, KKTS (62. μS/cm) followed by MSGGK (63.6 μS/cm). EC reflects the relative differences in the dilution of anthropogenic pollutants (Xu et al., 2015) due to the dilution factors in rain i.e., rain droplets having water content (Gioda et al., 2013); the higher the EC, the higher will be the ionic components in precipitation, and lower water content in rain droplets. The anionic and cationic species of rainwater, which follow the decreasing trend for an anion: SO_4^{-2} > NO_3^- > Cl^- > HCO_3^-, > F^-, cation: Ca^{+2} >Mg^{+2} > NH_4^+ > K^+, ≥ Na^+ at all study sites, clearly indicate the input of anthropogenic and natural components (Kulshrestha et al., 2005) in the environment of this region, depending on anthropogenic sources, atmospheric chemistry, and meteorological conditions (Galy-Lacaux et al., 2009). The input of natural and anthropogenic ionic species along with the corrosive effects of water (due to its acidic nature) seems to promote the seepage of water into the masonry materials, which are enriched with SO_4^{-2}, NO_3^-, Cl^-, F^- , Ca^{+2}, Mg^{+2}, Na^+, and K^+. The existence of water-soluble salts (particularly sodium chloride and sulphate salt) enriches these ionic species (Charola, 2000) in monumental structures, causing mineralogical and textural deterioration over time, with corrosive byproducts (salts) of these components due to an increase in moisture content (Mohamed, 2019). This is responsible for the hygroscopicity of materials and generation of crystallization and re-crystallization pressure within the materials (Hall & Hoff, 2002), which, when the resistance of the material is exceeded, will cause deterioration of materials.

Figure 4

Seasonal Analysis of Rainfall and Temperature over a Period of 42 Years (1976-2018) of Haryana Region, India



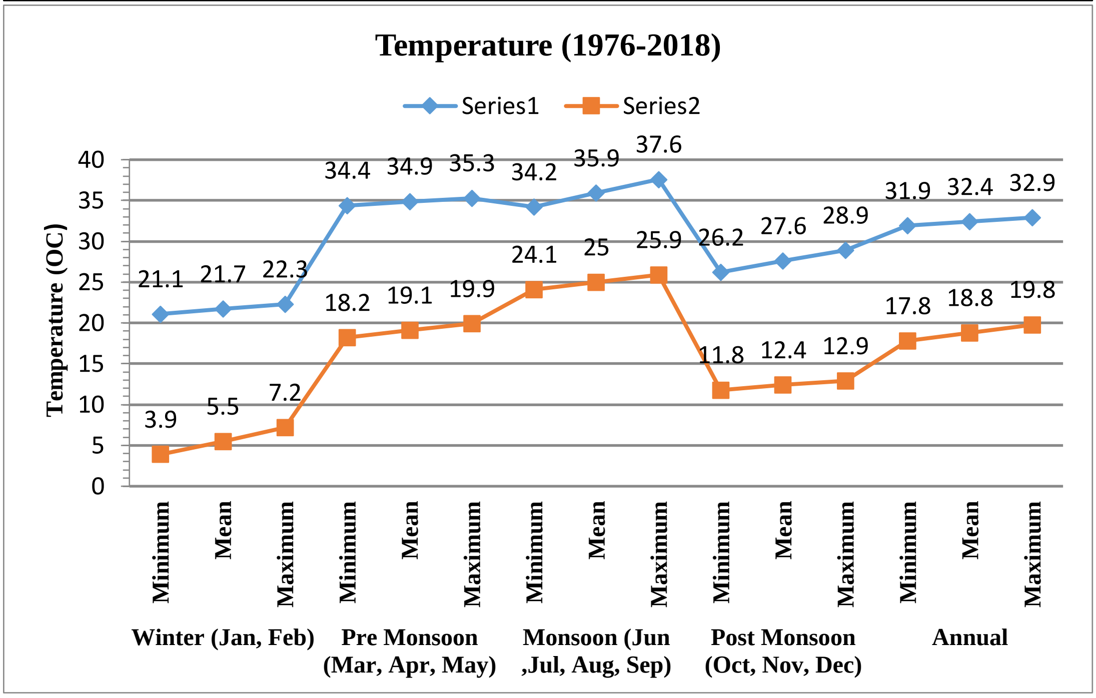


Figure 5

Projected Change in Rainfall and Temperature of Haryana Region, India

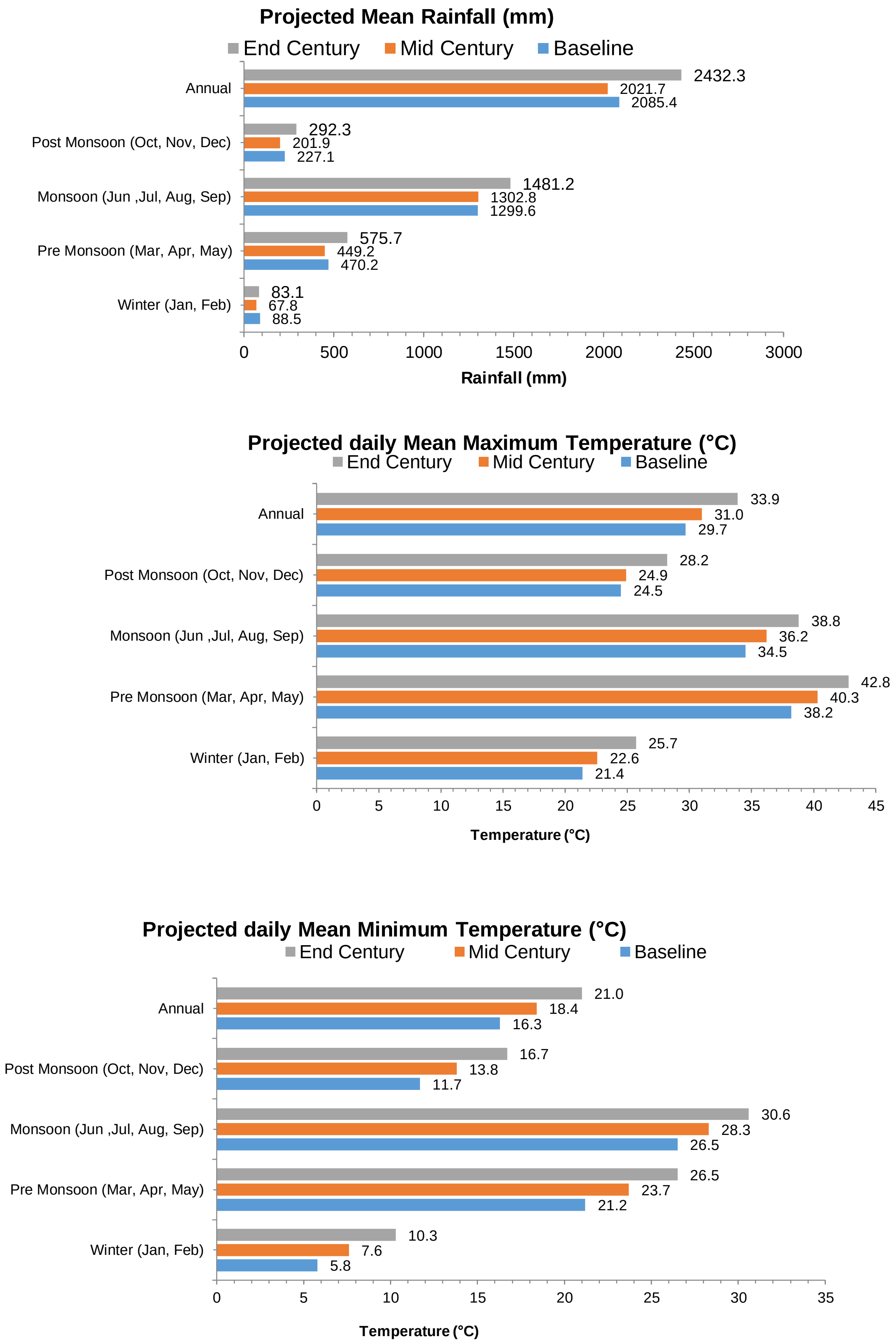


Table 3

Mean value (2016-2018) of rainwater pH, EC (μS/cm), and dissolved ions (μeq/l) around monumental structures of Haryana region, India

Study sites	pH	EC	Cl^-	SO_4^{-2}	NO_3^-	F^-	HCO_3^-	Na^+	K^+	Ca^{+2}	Mg^{+2}	NH_4^+
SCTTK (n=15)	6.02	62.3	28.9	78.1	49.4	2.6	9.6	20.2	20.8	147.6	69.0	62.7
MSGGK (n=15)	6.00	63.6	27.4	72.8	51.5	3.1	9.1	28.3	24.9	155.7	69.9	65.1
KBMP (n=15)	5.99	65.2	26.8	85.8	65.5	3.9	9.0	22.7	25.6	161.7	71.9	65.3
KKTS (n=15)	6.00	62.3	26.2	67.7	59.0	2.8	9.2	25.1	24.0	137.4	69.3	61.5
Mean	6.00	63.4	27.3	76.1	56.4	3.1	9.2	24.1	23.8	150.6	70.0	63.7

Impact due to climate change in future

Making clear predictions about the impact of different extrinsic environmental factors on deterioration of monumental structures is a difficult task. The current and projected scenarios of weather agents (rainfall and temperature) (Figure 4 & 5) of the region indicate temperatures and precipitation variability, which will influence the micro-environment of the monuments (Torres, 2004). The effect of this variability will accrue. The relative humidity and temperatures will damage the porous materials (salt action); the cycle of relative humidity will cause salts to go into the solution, and to be transported and reprecipitate (Qazi et al., 2019) (Figure 6A: SCTTK), which may strongly increase the risk of deterioration of materials as compared to the present status (Figure 6B: KBMP). Consequently, the current biocolonization patterns will change along with the growth of other vascular and non-vascular plant systems (Figure 6C: SCTTK, 6D: MSGGK), with manifest effects on biodeterioration and biodegradation as higher temperatures and precipitation will encourage faster development of microorganisms, especially with the availability of moisture with nutrients (controlling factors in biocolonization) in semiarid and arid environments (Rajkowska et al., 2014; Sterflinger & Pinar, 2013). Variable precipitation of study sites (2007-2018) (Figure 7), especially in the monsoon period, affects the ground water level, salinity, and soil moisture content of the area. Lower soil moisture causes drying and shrinkage of the ground level, observed as cracking in walls and foundations (Malik et al., 2016). Higher soil moisture and salt load content increase the risk of rising damp (Figure 6E: KKTS), with an increase in the transfer and precipitation of water-soluble salts (Gulker et al., 2004) (Figure 6F: MSGKK).

Durability and future possibilities

Brick is highly resistant to change. It is not literally resilient because when brick deteriorates, it does not return to its original state; however, the intrinsic physical and mineralogical properties of bricks are crucial to the durability of monumental structures. The mean values of physical parameters of fired-clay bricks are given in Table 4. They are quite consistent and compatible (except for IRA), indicating higher durability, which lowers the negative influence of water on bricks.

IRA reveals the quantity of water sucked in by the pores in bricks because of capillary tension, and it has an important effect on the interaction between the mortar and bricks (Kayali, 2005). The results indicate that the mean initial rate of absorption (IRA) of bricks varied from 2.6 kg m^{-2} min^{-1} (SCTTK) to 3.2 kg m^{-2} min^{-1} (MSGGK), indicating poor bonding strength, as an IRA value between 0.25 and 1.5 kg m^{-2} min^{-1} produces good bond strength (Rai & Dhanapal, 2013).

The mean value of water absorption (WA) of brick samples (MSGGK: 11.2 wt. % to KBMP: 13.1 wt. %) determines the durability of bricks with respect to weathering; a value below 20.0 wt. % provides better resistance to damage.

The apparent porosity (AP) values (SCTTK: 20.7 vol. % to KBMP: 23.2 vol. %) reveal the improved thermal insulating properties of used bricks. The bulk density (BD) (SCTTK: 1.9 g/cc to MSGGK and KBMP: 2.1 g/cc) reveal the durability of ancient brick samples, and values between 1.6 g/cc to 1.8 g/cc identify high-durability bricks (BIS, 2007; Bhattarai et al., 2018).

The largely consistent and compatible (except IRA) values of the different parameters of hydric properties for all the monumental bricks indicate higher durability with denser, harder, and improved crystallinity, which lowers the negative influence of water on bricks (Bhattarai et al., 2018; Bordia & Camacho-Montes, 2012).

The mean values of the compressive strength indicates the technological process available at the time of manufacture of bricks. (CS) of the brick samples varied from 19.8 N/mm^2 (KBMP) to 22.8 N/mm^2 (MSGGK), which provides the reason behind the durability of these huge earth-based structures, as the reported value of CS for better mechanical resistance of North India bricks is 20.8 N/mm^2 (Kaushik et al., 2007).

The mean value of LS, which indicates the expansion behavior during the firing process, varied from 0.39% (MSGGK) to 0.53% (SCTTK), which is indicative of good dimensional control.

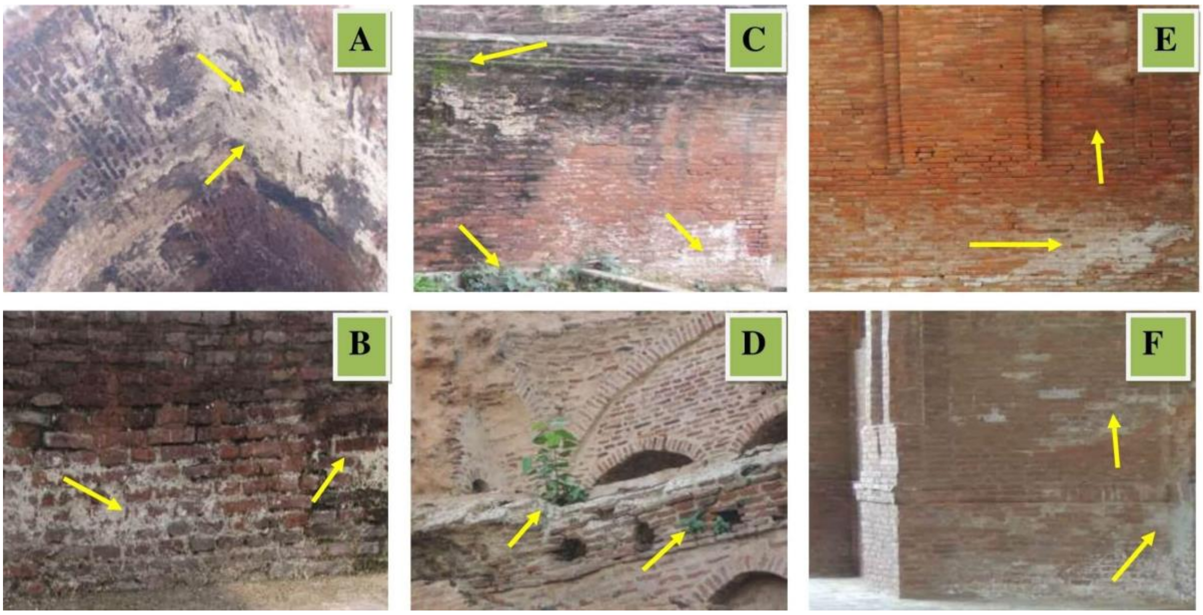
The elemental and mineralogical characterization of monumental bricks is shown in Figure 8, indicating that bricks were mainly composed of SiO_2 (~ 70%), Al_2O_3 (~ 14%) and Fe_2O_3 (~ 6%), and a low amount of flux (Na_2O, K_2O, MgO, TiO_2, MnO, and CaO). The XRD pattern of bricks exhibited prominent peaks of quartz, smectite, hematite, feldspar, and illite, and validates the elemental characterization. The XRD patterns do not contain any prominent peaks of calcite and dolomite phases; however, a small reflection of the calcite peaks is observed in brick samples (SCTTK: 1.98Å, 3.03 Å, MSGGK, KBMP, and KKTS: 3.03Å). The presence of maximum peaks of quartz and the absence of a prominent peak of calcite show that bricks were made from siliceous and non-calcareous earthen materials (clay) (Cardiano et al., 2004). The brick samples show the dominance of quartz (Si-O) due to peaks (Si-O absorption) in the region 779cm^{-1}-781 cm^{-1}, 471cm^{-1}-474 $cm^{-1}$and at 1080 cm^{-1} in all brick samples in addition to peaks at 688 cm^{-1} (SCTTK and KBMP) and 691 cm^{-1} (KKTS) (Saikia & Parthasarathy, 2010; Shoval & Beck, 2005). The Si-O-Al compounded vibrations in the region of 775cm^{-1}-780 cm^{-1} indicate the feldspar, which is clearly shown at 776 cm^{-1} (SCTTK and KBMP) (Jordan et al., 1999). The band at 533 cm^{-1} (SCTTK and KBMP) indicates Fe-O of Fe_2O_3 (hematite) (Budhathoki et al., 2018). The absence of the corresponding peaks in MSGGK and KKTS may be due to the overlap of absorption bands of silicates.

The mineral characterization reveals that the bricks used for constructing these monuments were of good quality, with resistance to cracking and spalling as the high content of SiO_2 and Al_2O_3 decreased the shrinkage and increased the refractoriness and mechanical strength, while Fe_2O_3 and TiO_2 content offer higher plasticity and mechanical strength to these bricks (Rai & Dhanapal, 2013; Shrestha, 2017). The high quartz content is the main factor responsible for low plasticity and high Young's modulus (Desire et al., 2017), which are associated with mechanical strength of masonry. The absence of prominent peaks of calcite and dolomite, with other mineral phases, indicates that bricks have good mechanical and physico-sintering properties (Sokolar et al., 2012).

The physical properties Show that, although the bricks have hydraulic nature, the low shrinkage and mechanical resistance along with the mineralogical characteristic comprise the main driving forces of the resistance capacity and mechanical strength of the monuments toward the adverse effect of climatic factors for such a long period. These results also reveal that, in the future, the input of natural and anthropogenic ionic species from rainwater and hydric properties of bricks in addition to micro-environment may accelerate deterioration of the bricks and binding materials (mortar), causing failure of the bricks and mortar joints.

Figure 6

Present and expected future deterioration



Note. Efflorescence of salt (A, B, C, E & F), growth of vascular and non-vascular plant systems (C & D), dampness (C & E), salt action (C & F)

Figure 7

Study Sites Wise Mean and Annual Rainfall (2007–2018)

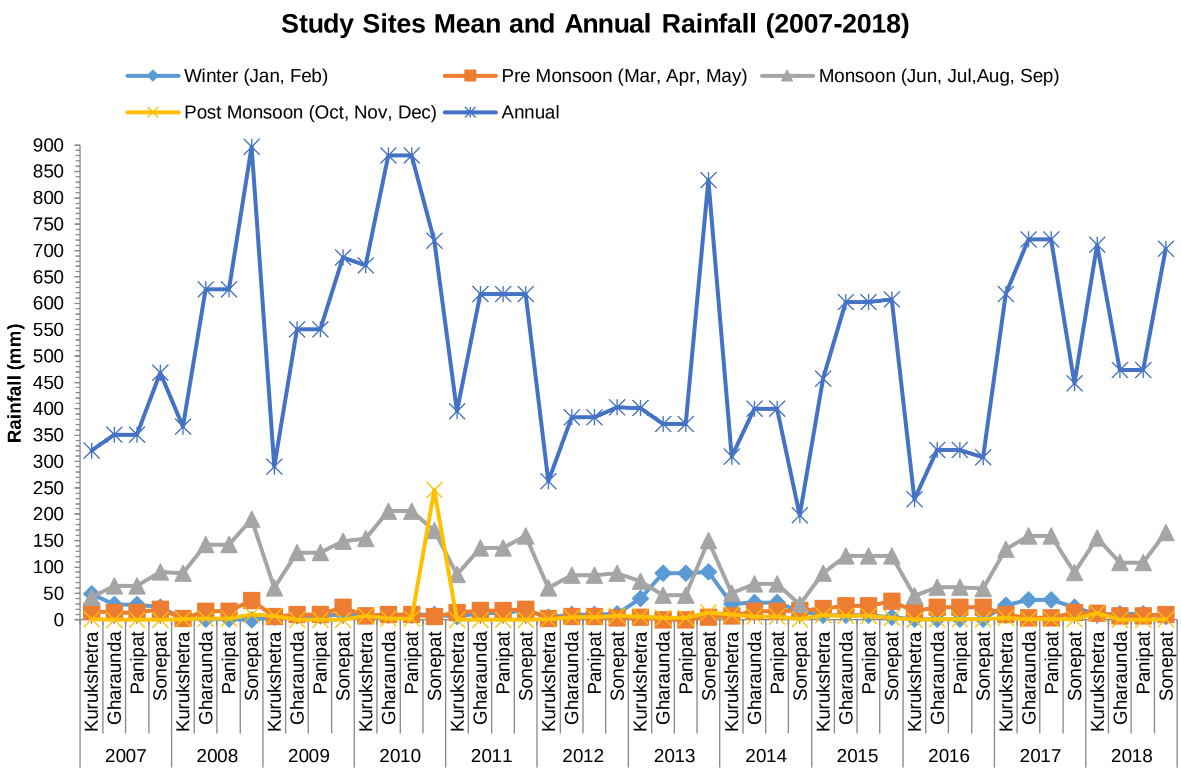


Table 4

Mean value of physical behavior of bricks of monumental structures of Haryana region, India

Study sites	**Initial rate of absorption (IRA) (kg m^3 min^{-1})**	**Water absorption (WA) (wt. %)**	**Apparent Porosity (AP) (vol. %)**	**Bulk density (BD) (g/cc)**	**Compressive Strength (CS) (N/mm^2)**	**Linear Shrinkage (LS) (%)**
SCTTK (n=3)	2.6	11.4	20.7	1.9	20.9	(-)0.53
MSGGK (n=3)	3.2	11.2	21.1	2.1	22.8	(-)0.39
KBMP (n=3)	3.1	13.1	23.2	2.1	19.8	(-)0.46
KKTS (n=3)	2.8	12.6	22.6	2.0	20.1	(-)0.51
Mean	2.9	12.0	21.9	2.0	20.9	(-)0.47

Adaptation possibilities for improved durability

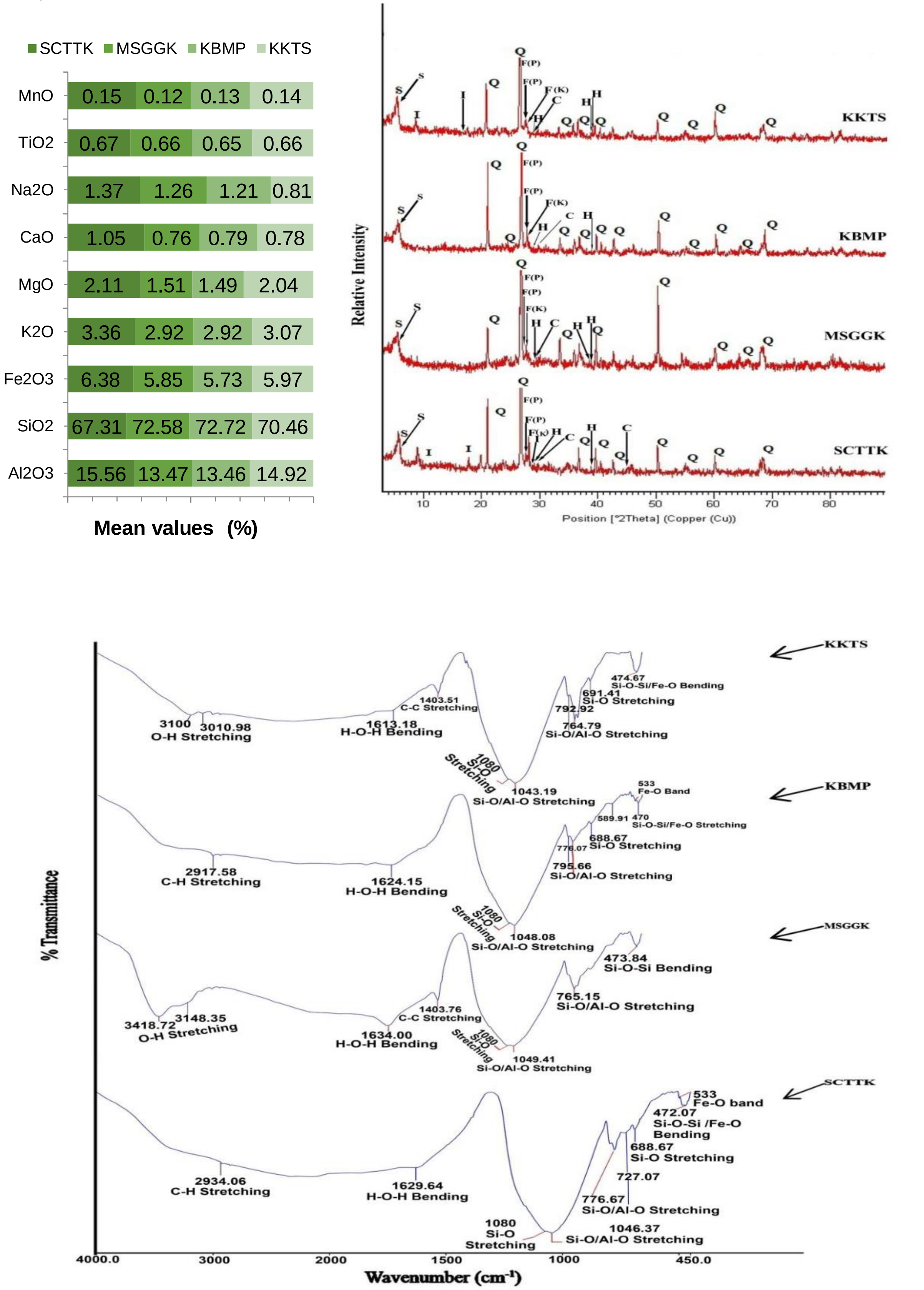
The key factor in the management of monumental structures is to maintain the intrinsically stable and resilient environment around the monuments, which helps maximize the monuments' tendency to "remain stable" (Nijland et al., 2010). To minimize the impact of climatic change on used masonry materials, different possibilities might be adapted, understanding that such adaptations may be complicated by the fact that impacts may behave in unpredictable ways with different materials (Moncmanova, 2007).

Restoration masonry materials based on additive manufacturing with smart materials may also be used as an adaptive measure (Kumar et al., 2019) to minimize the climatic change impact. The changing climatic situation will significantly affect the temperature and moisture balance of monuments, causing varying levels of expansion and other effects in masonry materials. Structural modification of monumental structures with the use of phase change materials (PCMs) to enhance the thermal storage capacity of traditional building materials (Frigione et al., 2019) can be used as an alternative to lower the temperature within monumental structures.

The combined effect of temperature and precipitation of the region in relation to the physical (hydric) properties of used materials is likely to speed up the effects of biocolonization. The use of low water retention masonry materials may serve to check the effect of biocolonization. Visually, it was observed that it is not easy to predict the effect of soluble salts on masonry materials. Moreover, their synergistic effects call for innovative approaches toward adaptation possibilities. Higher temperatures and precipitation may result in deeper penetration of water and faster evaporation that will potentially dissolve more salts, and their transportation and accumulation within masonry materials (Moncmanova, 2007). So, the use of more salt-resistant materials (restoration plasters or bricks), with a pore structure favoring efflorescence (salt crystallization at the surface) rather than crypto-efflorescence (salt crystallization below the surface) may be useful (Lubelli & Hees, 2007). Fly ash-sand-lime bricks can be used as an alternative masonry

Figure 8

Elemental Oxides (%), Mineralogical Composition (Q -Quartz, I- Lllite, S-Smectite, H- Hematite, F (P) - Plagioclase Feldspar, F (K)- K-Feldspar, and C-Calcite and FTIR Spectra of Monumental Brick Samples



material because of their pozzolanic and increased cementation properties (Shruti & Patil, 2015; Subramaniam, 2016) with economic, ecological, and technical aspects. In addition to this the use of mixture of restoration mortars and crystallization inhibitors will also be useful in minimizing the adverse effects of salt actions (Delgado et al., 2016).

CONCLUSIONS

The study highlighted the climatic conditions, levels of deterioration, environmental envelope of the monumental structures, and geochemical characterization of used fired clay bricks. The differences in climate scenarios indicate that. in the future, the tendency towards deterioration of monumental structures might be increased in term of biocolonization and salt crystallization. The rainwater characterization reveals that water-soluble salts may penetrate the porous masonry materials, causing increased hygroscopicity of materials and generation of crystallization and re-crystallization pressure within materials. The physical properties and mineralogical characterization are of utmost importance to the longevity and durability of these structures. The deterioration tendency can be minimized by adopting a sustainable approach towards planning, design, operation, and management of environmental parameters. The continuous monitoring of the actual impact and uses of suitable compatible masonry materials for conservation and restoration activities may be adopted for sustainability of monumental structures. Monitoring can be used to generate reference data about the progress of decay, and to identify the need to adopt more sustainable management approaches in order to foster and forecast the longevity and durability of monumental structures. To enhance the long-term management and sustainable conservation in the changing climatic conditions, it is pertinent to establish a link between masonry structures and the Action Plan on Climate Change.

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