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Heritage clay brick characterization and assessment with compatible contemporary bricks for retrofitting of heritage monuments

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Abstract. Various Mughal architecture clay brick masonry monuments were built in the northern Indian state of Punjab from the late 14^{th} to the late 19^{th} century. Nanakshahi monuments (era of the 1^{st} Sikh Guru: Guru Nanak Dev Ji) are gigantic clay brick masonry structures constructed of lime and lime surkhi mortar (a powdered form of red burnt clay brick). Currently, this study is focused on identifying a suitable material for repairing and strengthening heritage clay brick monuments. Using the chemical composition of heritage Nanakshahi clay bricks (NSCB), the study compares them with contemporary clay bricks (CCB) from the same region and then compares them to newly prepared clay bricks (NPCB), which have similar composition and dimensions to NSCB. The X-ray fluorescence confirms that the NSCB samples from southeast Punjab have an elemental composition consisting of filler SiO_2 and binding elements such as Al_2O_3, Fe_2O_3, CaO, K_2O and MgO. The average density of ancient NSCB and CCB is found to be similar; the ancient NSCB has a lower water absorption rate and porosity in contrast to the present-day clay bricks. The initial rate of absorption (IRA) of an ancient NSCB is quite high. In comparison to the heritage NSCB, the CCB's compressive strength value is lower and the uniaxial compression strength of newly prepared clay bricks (NPCB) with similar chemical composition and dimensions is comparable to that of the heritage NSCB from Punjab districts. The significance of the study is to suggest a compatible material for strengthening heritage clay brick monuments in northern India.

Keywords: Nanakshahi clay bricks, heritage monuments, Punjab, X-ray fluorescence, uniaxial compressive strength

Classification numbers: 2.9.2, 2.9.4, 2.10.3.

1. INTRODUCTION

Heritage structures and monuments are the country's assets and reflections of its culture. These structures should be given appropriate consideration as they are vulnerable to lateral seismic loads [1, 2]. Heritage monuments are important for our future generations from the perspective of inculcating knowledge based on ancient structural configurations and the structural behavior of masonry. The northwestern state of Punjab (India) has various enormous stand-alone heritage monuments in clay brick masonry that are required to be preserved. The four districts of the southeastern Punjab considered for the present study are, Fatehgarh Sahib (Sirhind), Ludhiana, Patiala and Malerkotla, each of which has a rich historical background. During the 12th century, Sirhind was under the rule of the Hindu Chauhan Rajputs of Delhi and later in the 14th century, during the Mughal Empire, Sirhind served as the headquarters of the Mughal administration in Eastern Punjab. This historic and pious town was transformed into a district in the 20th century, named Fatehgarh Sahib after Sahibzada Fateh Singh, the youngest son of Guru Gobind Singh Ji. Among the various heritage monuments, some are caravan sarais and tombs built during the Mughal Empire, including the Mosque of Sadna Kasai (MSQ), Aam Khas Bagh (AKB), Haweli Todar Mal (DTH), Rauza Sharif (RS), Tomb of Ustad (TOU) and Tomb of Shagird (TOS) which are among those that are still surviving today in the historical city of Fatehgarh Sahib. Fatehgarh Sahib is located between Ludhiana and Patiala in the north and Malerkotla in the south; it shares a border with all three cities. In 1480, the Lodhi dynasty of the Delhi Sultanate founded Ludhiana. A village named Mir Hota was originally named Lodhi-ana, meaning "Lodhi town" and was later renamed "Lodiana" and is now known as Ludhiana. There are only a few surviving structures from this period in the city, including Serai Lashkari Khan (SLK) and Mughal Caravan Serai (MS). The city of Patiala is located in the southeastern part of Punjab, in the north-western part of the country. In 1763, Ala Singh established the royal dynasty of Patiala State and Patiala is named after him. The city's center is situated around Qila Mubarak (QMP), sometimes called the 'Fortunate Castle' because of its location. Sheikh Sadruddin-i-Jahan from Afghanistan established the Muslim majority state of Malerkotla in 1454. It was carved out of Sangrur district in 2021, along with some adjacent areas, to form Malerkotla district. The heritage monuments of Malerkotla, including Qila Rehmatgarh (QR) and Sheesh Mehal (SM) are among its most famous features.

Burnt clay bricks were used in the construction of masonry monuments during the Mughal Empire in Punjab in the late 14th to19th centuries. Hand-molded, sun-dried burnt clay bricks have been used since ancient civilizations and their property characterization is vital for strengthening structures from future calamities. Property characterization is a challenging task due to the difficulty faced during the collection of samples. As some contemporary materials may not be compatible in terms of the characterization of their properties, an assessment of their physical and mechanical properties is essential. Contemporary clay bricks are not suitable for strengthening heritage monuments due to their intrinsic mechanical property and dimensional variations, which further adversely, affect their aesthetics.

The homogeneous and durable clay brick has been a fundamental building construction material since the Roman and Egyptian eras [3, 4]. Few studies have been conducted and reported on the characteristics of historic clay bricks, such as their seismic venerability, chemical degradation and environmental pollution [5, 6]. It has been found that historical clay bricks are very durable and tough because of their superior mechanical properties, physical properties and chemical compositions [7]. In Punjab, the aesthetics of identified heritage monuments provide a glimpse of Mughal architecture constructed during the period 1526 AD to 1800 AD (the Mughal period) [8], but there is still no research carried out in this geographical location for the said purpose. Heritage buildings were found to be constructed using flat clay brick masonry (local dialect: Nanakshahi brick) with lime surkhi mortar [9, 2].

In this study, 13 heritage sites were identified in the southeastern Punjab region (Fatehgarh Sahib, Patiala, Malerkotla and Ludhiana) [9] (Figure 1). Interactions with local people and previously published studies were used to gather information about heritage monuments within the southeastern Punjab region. The precise map representation of the exact location of the selected heritage monument sites, their historical significance, construction year and the number of clay brick samples that were collected are presented (Table 1). The samples of loosely extractable heritage Nanakshahi clay bricks (NSCB) were collected. Brick kilns in the region were also identified and contemporary clay brick (CCB) samples from these identified brick kilns were also collected. The newly prepared clay bricks (NPCB) of 1st-class classification as per Indian standards were obtained from the brick kilns located in selected Punjab districts. The property characterization and comparison of the heritage NSCB, CCB and NPCB of the southeastern region of Punjab are presented.

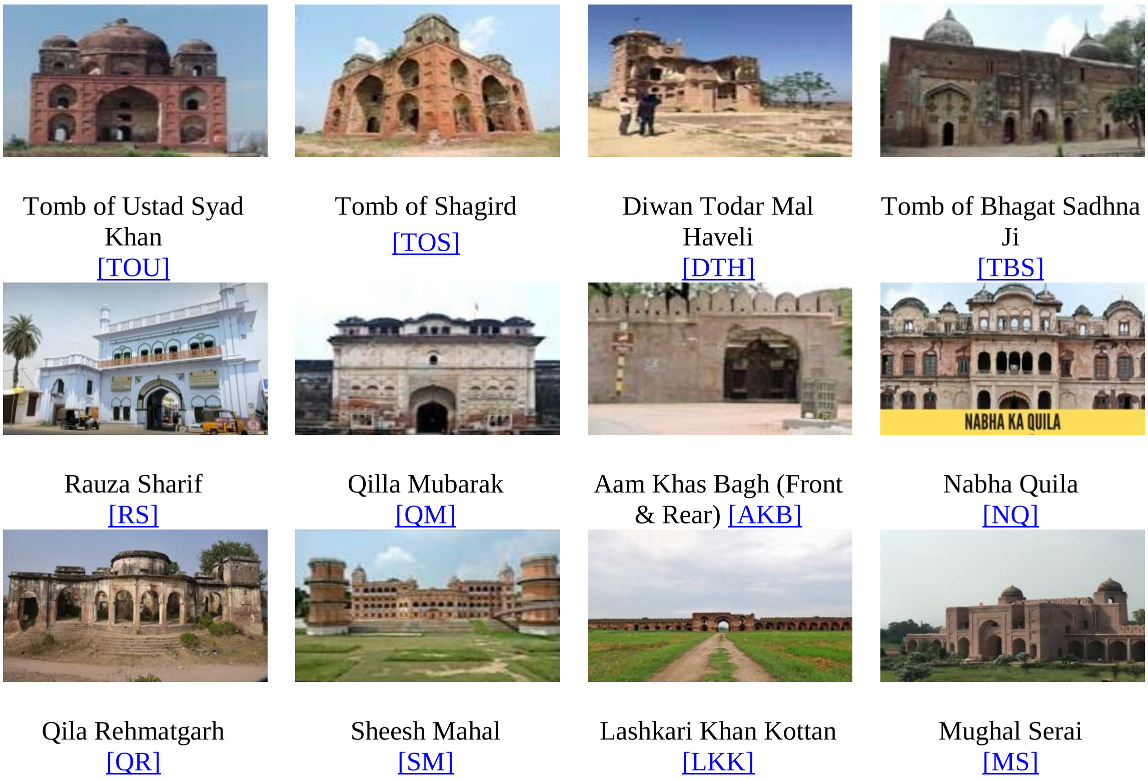

Figure 1. Identified heritage monuments.

The objective of the current study is to address the physical-mechanical property characterization of clay bricks at the selected heritage sites, property comparison of heritage Nanakshahi clay bricks with newly prepared clay bricks produced using similar chemical composition[9] and dimensions as those of Nanakshahi clay bricks and contemporary clay bricks used nowadays in the southeastern region of Punjab and finally to recommend compatible clay bricks in terms of composition and dimensions for repairing and strengthening the heritage monuments.

Table 1. Details of heritage monuments with historical significance [9].

Site name with precise map location	History and year of construction	No. of sample collected
Tomb of Ustad Syad Khan [TOU]	In 1710 to avenge the killings of young sons and mother of Guru Gobind Singh, a warrior Banda Singh Bahadur and his sikh army destroyed the city of Sirhind completely but some of the monuments like the Tombs of Ustad and Tomb of Shagird survived (18^{th} century).	6
Tomb of Shagird[TOS]	History of the monument is same as above and it is approximately few hundred meters away from Tomb of Ustad Syad Khan.	8
Diwan Todar Mal Haveli [DTH]	Diwan Todar Mal Haveli popularly known as Jahaz Haveli or Jahaz Mahal is the 17^{th} century residence of Todar Mal Jain, an ardent follower of the Sikh Gurus, most remembered for defying the Mughals by arranging the cremation of young martyred sons of Guru Gobind Singh and his mother (17^{th} century).	7
Tomb of Bhagat Sadhna Ji [TBS]	The Mosque of Sadhana Kasai is a unique mosque built of Nanakshahi bricks with art paintings on walls. This tomb was dedicated to the memory of Bhagat Sadhna Ji, also called Sadhna Qasai and was a northern Indian poet, saint, mystic and one of the devotees whose hymn was incorporated in Guru Granth Sahib. He spent his last days in the town of Sirhind (14^{th} century).	7
Rauza Sharif [RS]	Rauza Sharif or Dargah of Sheikh Ahmed is situated on the Sirhind-Bassi Pathana road in the vicinity of Gurudwara Fatehgarh Sahib. Sheikh Ahmed Farooqi lived at this place during the times of Akbar and Jahangir from 1563 to 1624 AD. The death anniversary of the Mujadid is held here for more than 300 years and is largely attended by Muslims from across the world (17^{th} century).	4
Qilla Mubarak [QM]	Qilla Mubarak was first built as a 'Kachigarhi' (Mud fortress) by Baba Ala Singh in 1763, who was the founder of the Patiala dynasty. Later, it was reconstructed in baked bricks. The interior portion of Quila, which is known as Quila Androon is built by Maharaja Amar Singh (18^{th} century).	4
Aam Khas Bagh (Front & Rear) [AKB]	This Royal inn was constructed by Babur and rebuilt by Mughal Emperor Shah Jahan for the use of royal family as well as common people. Initially built along the Mughal military road between Delhi and Lahore but was later also used by the Royal couple for halts during their, to and from movement between Delhi and Lahore (16^{th} century).	8 & 5
Nabha Quila [NQ]	The foundations of the Nabha Quila were laid around 1760 AD. Additions were constructed on the eastern and south-eastern edges of the Quila complex now known as Hira Mahal and Ripudaman college Nabha (18^{th} century).	12
Qila Rehmatgarh [QR]	Qila Rehmatgarh is a place with historical importance built in the year 1850 by Nawab Rahmat Ali Khan, a fortress located at Nabha road in Malerkotla. Remnants of the fort remain located on land owned by the Ministry of Defence (19^{th} century).	8
Sheesh Mahal [SM]	The Sheesh Mahal or Palace of Mirrors, another significant attraction of the Patiala region. This palace was built by Maharaja Narinder Singh in 1845, with extensive use of glass. It is constructed in a forest area and is surrounded by gardens, fountains, terraces and an artificial lake. In ancient times, it used to be the presidential palace of the Nawab of Malerkotla (19^{th} century).	6
Lashkari Khan Kottan [LKK]	Serai Lashkari Khan located near Gurdwara Manji Sahib, Kotan (near Doraha) in Ludhiana District, Punjab, India is a historic inn built by the Mughal military general Lashkari Khan, in the reign of Emperor Aurangzeb in 1667 CE (17^{th} century).	4
Mughal Serai [MS]	Doraha Serai was built as Mughal caravanserais by the Mughal ruler Jahangir. Once an example of fine Mughal architecture, this historical serai is in a dilapidated condition due to the in different attitude of the government (17^{th} century).	6

2. MATERIALS AND METHODS

The working methodology to achieve the objectives of the present study is presented in the form of a flowchart (

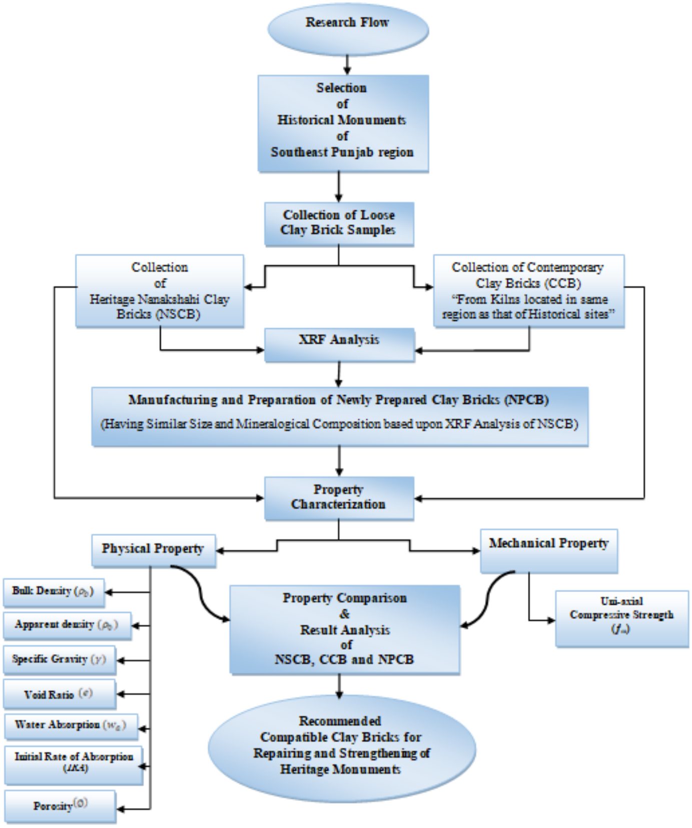

Figure 2). In the current study, loose extractable heritage NSCB samples were collected from each heritage monument in the southeastern districts of Punjab (Figure 1) such that the aesthetics were not disturbed. The unadorned samples (without frogs) with minor differences in size due to different site locations were collected from 13 identified heritage monuments. The heritage monuments were identified and selected by visiting particular sites based on their location, feasibility and ease of sample collection. Initially, the clay brick samples collected were visually examined for

shape, color and surface texture and thereby determined for the average unit weight and dimensions (Table 2). Due to rudimentary transportation infrastructure in that century, it is assumed that the locally available raw material was used during the manufacturing process of these clay bricks. Hence, the present study uses hand-molded clay bricks made from locally available clay earth according to the traditional process and with similar dimensions and elemental compositions to the traditional clay bricks [9]. The historical NSCB with length, width and thickness ranging from 9-23.3 cm, 6.5 - 12.4 cm and 3-3.9 cm, respectively, were taken from historical monuments (Figure 3), while the hand-molded CCB with length, width and thickness in the range of 22.3 - 22.5 cm, 10.5 - 10.6 cm and 6.9 - 7.1 cm, respectively, were collected from the identified brick kilns in that particular region. The NPCB having similar dimensions and composition as NSCBs (evaluated from XRF) was manufactured (Figure 4 (a)-(d)).

Figure 2. Flow diagram of present study.

Figure 3.Collected heritage Nanakshahi clay bricks (NSCB) from selected sites (thickness: 3 - 3.9 cm).

(a) (b) (c) (d)

Figure 4.Newly prepared clay bricks (NPCB) from selected districts (thickness: 3 cm).

Table 2.Details of identified heritage monuments and collected clay brick units.

Sr. No.	**Century of construction**	**Location / District**	**Name of heritage monuments**	**Average size of collected Nanakshahi clay brick units (mm)**			**Average unit weight (Kg)**
				Length (mm)	**Width (mm)**	**Thickness (mm)**	
1	14^{th}	Sirhind / Fatehgarh Sahib	Mosque of Sadna Kasai (MSQ)	175	99	30	0.971
2	16^{th}		Aam Khas Bagh (AKB)	210	95	32	1.32
3	16^{th}		Aam Khas Bagh (AKB rear part)	202	102	38	1.312
4	17^{th}		Haweli Todar Mal (DTH)	193	113	36	1.441
5	17^{th}		Rauza Sharif (RS)	170	82	32	0.741
6	18^{th}		Tomb of Ustad (TOU)	207	108	35	1.208
7	18^{th}		Tomb of Shagird (TOS)	233	119	36	1.611
8	19^{th}	Malerkotla / Malerkotla	Sheesh Mehal (SM)	154	95	37	0.971
9	15^{th}		Qila Rehmatgarh (QR)	157	99	35	0.992
10	17^{th}	KotPanaich / Ludhiana	Serai Lashkari Khan (SLK)	206	115	39	1.804
11	17^{th}	Doraha / Ludhiana	Mughal Caravan Serai (MS)	198	124	34	1.588
12	18^{th}	Patiala / Patiala	Qila Mubarak (QMP)	90	65	32	0.289
13	18^{th}	Nabha / Patiala	Nabha Qila (NQ)	153	94	31	0.943

As part of the investigation of the heritage Nanakshahi clay bricks (NSCB) collected from selected historical monumental sites, the X-Ray Fluorescence (XRF) analysis was conducted using a fully computerized non-destructive XRF analyzer (Bruker, S8 Tiger) for determination of mineral compositions in percentage, as well as molecular structure and compound names. The study mainly emphasized the physical and mechanical property characterization of the collected heritage NSCB, 1st class CCB and NPCB. The sampling and property characterization of clay bricks were carried out in accordance with ASTM C20 and ASTM C67 [10, 11]. The experimental testing was conducted in specific laboratories under controlled conditions using relevant equipment (weighing balance, oven, water bath, etc.) and formulas.

3. RESULTS AND DISCUSSION

There are certain parameters that must be considered in order to select the most appropriate strengthening material for a particular intervention. The findings of the study indicate that there are significant challenges in assessing and comparing heritage clay bricks with contemporary clay bricks due to their different chemical, physical, and mechanical characteristics. New prepared clay bricks were manufactured using similar dimensions, mineral compositions and locations as heritage Nanakshahi clay bricks, for use as a suitable strengthening material for heritage monuments. Their properties were compared with those of the heritage Nanakshahi and contemporary clay bricks. Despite the fact that the maximum parameters were evaluated in the present study, the seismic vulnerability of the study area and the lack of availability of past deterioration data pose a challenging situation. The present study parameters are discussed as follows:

3.1. Physical properties

The clay brick samples collected from heritage masonry structures were surface-cleaned of loose dust, soil and lime-surkhi mortar using an air compressor. The heritage NSCB and CCB properties, namely initial rate of absorption (IRA), apparent density (ρ_0), bulk density (ρ_b), specific gravity (γ), void ratio (e), water absorption (w_a) and porosity ($\emptyset$)were determined. The physical properties of the heritage NSCB and their comparison with the CCB and NPCB are presented in (Table 3) and (Table 4). Similarities in physical properties between the NPCB and heritage NSCB of the Punjab region are possibly due to the same region soil type and similar mineral compositions used during the production of the NPCB. The authors evaluated these property parameters for the heritage NSCB in the present study as a means of identifying clay bricks with similar properties that may be used for the repair of damaged heritage monuments.

As determined by laboratory testing of the NSCB, CCB and NPCB under controlled conditions, the heritage NSCB of the southeastern Punjab region possesses properties such as bulk density (ρ_b) apparent density (ρ_0), specific gravity(γ), void ratio(e) water absorption (w_a), initial rate of absorption (IRA)and porosity ($\emptyset$) that range from 1514 kg/m^3 to 2447 kg/m^3; 1511 kg/m^3 - 2444 kg/m^3; 1.99 - 2.31; 17.34 % - 33.58 %; 8.29 % - 14.57 %; 17.49 g/cm^2/min - 60.20 g/cm^2/min; and 11.40 % - 28.64 %, respectively; while for the CCB they are in the range of 1156 kg/m^3 - 1485 kg/m^3; 1148 kg/m^3 - 1474 kg/m^3; 1.51 - 1.72; 21.63 % - 33.85 %; 11.30 % - 13.48%; 58.59 g/cm^2/min - 91.05 g/cm^2/min; and 18.06 % - 22.45 %, respectively; and in comparison with the NPCB of the same region these properties lie between 1811 kg/m^3 and 2000 kg/m^3; 1807 kg/m^3 and 1997 kg/m^3; 2.32 and 2.55; 17.88 % and 36.19 %; 11.96 % and 10.56 %; 28.83 g/cm^2/min and 43.60 g/cm^2/min; 20.39 % and 22.63 %, respectively. There is a great deal of similarity between the physical properties of the NPCB and NSCB due to the similarity in dimensions, regions and composition of the clay mix used in the manufacture of the NPCB. Consequently, the percentage of moisture and sand in the mix, size and shape of the pores and the temperature at which the clay bricks are initially fired all contribute to improving their properties [12, 13].

3.1.1 Bulk density($\boldsymbol{\rho_b}$)

The bulk density is a key parameter as it indicates the weight of the brick. The greater the bulk density (ρ_b), the stronger the clay brick. The heritage NSCB has a bulk density (ρ_b) value ranging from 1514 kg/m^3 to 2447 kg/m^3, with an average of 1820 kg/m^3. The study explored that the NSCB samples collected from the Todar Mal Haweli (TMH) [local dialect, named Jahaz Haweli] have the highest bulk density (ρ_b) while the NPCB samples from the Tomb of Ustad (TOU) [Ustad di Mazar] have the lowest bulk density (ρ_b).

The bulk density (ρ_b) of 1311 kg/m^3 was determined for the CCB of the Punjab region, which can be further improved by adjusting the sand content and moisture content of the mix. The average bulk density (ρ_b) of the NPCB in the Punjab region was determined to be 1892.75 kg/m^3, with a minimum of 1811 kg/m^3 for Ludhiana and a maximum of 2000 kg/m^3 for Malerkotla district. The review of the literature reveals that very little research has been conducted on the bulk density of ancient clay bricks throughout the world and none has focused on this specific region of India. Based on the reviewed literature, in other developing nations like Nigeria an average bulk density (ρ_b) of 1818 kg/m^3 is determined [14], Kathmandu's ancient archaeological clay brick bulk density (ρ_b) ranges from 1200 kg/m^3 to 1750 kg/m^3 [15], while that of Iranian ancient clay bricks ranges between 890 kg/m^3 and 1520 kg/m^3 [16] and the bulk density (ρ_b) of the clay bricks in Afyon, Turkey is 1050 - 1150 kg/ m^3 [17]. Based on the preceding data, it is shown that the current study value compares well with the other studies across the world.

3.1.2 Apparent density ($\boldsymbol{\rho_0}$)

Since clay brick specimens are amorphous, the water absorption (w_a) test value of the clay bricks helps determine their apparent density (ρ_0) of clay brick. The apparent density(ρ_0) of the heritage NSCB varies from 1511 kg/m^3 to 2444 kg/m^3 with an average of 1817 kg/m^3. It is found that the clay brick sample from the heritage monument Tomb of Ustad (TOU), in Fatehgarh Sahib district exhibits the lowest apparent density (ρ_0), while the sample from the Todar Mal Haweli (TMH) heritage monument exhibits the highest apparent density (ρ_0). The CCB in the selected districts has an apparent density (ρ_0) ranging from 1148 kg/m^3 to 1474 kg/m^3, with a mean value of 1301.6 kg/m^3. The NPCB has an average apparent density (ρ_0) of 1889.76 kg/m^3, with a minimum and maximum of 1807 kg/m^3 and 1997 kg/m^3 for the districts of Ludhiana and Malerkotla, respectively. On reviewing the literature, it has been found that in European heritage monuments built between the 12th to 18th centuries, the apparent density of ancient clay bricks ranges from 1400 kg/m^3 to 1900 kg/m^3 [3]. This corresponds well with the apparent density (ρ_0) of clay bricks used in Punjab districts for heritage monuments, although a slight variation may be due to the difference in manufacturing process [18].

3.1.3 Specific gravity ($\boldsymbol{\gamma}$) *and void ratio* (e)

The density of an element can be fairly assessed using its specific gravity (γ), which is a prime engineering property. Clay bricks collected from the heritage structures have an average specific gravity (γ) of 2.22. The clay brick samples collected from Nabha Quila (NQ) have the highest value of 2.31, while the clay brick samples collected from Aam Khas Bagh (AKB) have the lowest value of 1.99. A slight variation in specific gravity (γ) was observed between the heritage NSCB and CCB, with values ranging from 1.51 to 1.72 with an average of 1.62. The NPCB has a maximum specific gravity (γ) of 2.55 for Malerkotla, a minimum of 2.32 for Ludhiana and an average of 2.42 for the southeastern Punjab region, slightly higher than the NSCB's.

The specific gravity (γ) influences the void ratio (e) and saturation degree[19]. The NSCB samples collected from TOU and AKB have the highest and lowest void ratios of 33.58 % and 17.34 %, respectively, with an average value of 26.95 %, which is slightly lower in comparison with the CCB, with an average of 27.81 %, higher than the NPCB which has an average of 25.79 %. This slight variation could be attributed to the particle size, quantity and firing temperature of clay used during clay brick manufacturing [20].

3.1.4 Water absorption($\boldsymbol{w_a}$)

Clay brick constitutes a considerable amount of pores by volume, which makes it susceptible to cracking, deterioration and strength reduction due to freezing and thawing. Furthermore, the reaction of water with soluble salts results in the aesthetic degradation of clay brick surfaces and efflorescence. Hence, water absorption (w_a) in clay bricks is an indispensable physical property expressed as a percentage relationship of the absorbed weight of water to the dry weight of the specimen and is required to be determined. Average water absorption (w_a) of 11.71 %, with a minimum of 8.29 % and a maximum of 14.57 %, was determined for the heritage NSCB of the late 14th to early 19th century monuments in the southeastern Punjab region. The CCB of the same region showed an average of 12.20 %, a minimum of 11.30 %, and a maximum of 13.48 %. The average water absorption of 11.3 % was obtained for the NPCB, which is almost similar to the NSCB, with maximum and minimum values of 11.96 % and 10.56 % for Patiala and Malerkotla, respectively. On reviewing the literature, a significant variation in water absorption (w_a) is observed worldwide, as the values lie between 20.1 and 24.9 % for the red and brown ancient clay bricks from the 8th to 13th centuries in Italy [21]. The values of 18 - 19 % and 12 – 24 % were found for the heritage clay bricks from the 9th to 10th centuries and in the 13th century, respectively [22]. The water absorption (w_a) lies between 6 and 32 % for historical clay bricks from the 12th to 18th centuries[6]. The water absorption (w_a) range lies between 6.7 and 12.6 % as quoted for ancient Roman clay bricks from the 3rd to 5th centuries and ranges between 19.0 and 22.0 % for the later period between the 10th and 19th centuries in Toledo, Spain [23].

*3.1.5 Initial rate of absorption (**IRA**)*

The initial rate of absorption (IRA) is defined as the amount of water absorbed in one minute over 193.548 square centimeters of clay brick bed area. The initial rate of absorption (IRA) and water absorption (w_a) are generally determined to help in mortar choice and efficient handling of materials during construction activities. Extremely high and extremely low (IRA) are not suggestible for obtaining acceptable adhesion among the mortar and clay bricks and hence influence the durability and bending resistance of the masonry [24, 25]. An average IRA of the Mughal period NSCB is determined to be 37.34 g/cm^2/min, with a minimum of 17.49 g/cm^2/min for Aam Khas Bagh (AKB) in Fatehgarh Sahib district and a maximum of

60.20 g/cm^2/min for Quila Rehmatgarh (QR) in Malerkotla district. In contrast, the average IRA of the CCB is determined to be 70.54 g/cm^2/min, with a minimum and maximum of 58.59 g/cm^2/min and 91.05 g/cm^2/min for Fatehgarh Sahib district and Malerkotla district, respectively. The NPCB has a minimum and maximum IRA of 28.83 g/cm^2/min and 43.60 g/cm^2/min, respectively, for Malerkotla and Patiala, with a mean of 38.45 g/cm^2/min in the southeastern Punjab region, which is similar to the NSCB due to its similar composition. It is conjectured that the variation in the values may be due to the adoption of a separate process followed during the manufacturing of clay bricks. The clay brick specimens with an initial rate of absorption (IRA) lying between 10 and 30 g/cm^2/min result in an adequate bond strength with suitable mortar [26]. As the average IRA value obtained is greater than 30 g/cm^2/min, the clay bricks must be well saturated before laying to avoid poor adhesion because of the prompt suction of water into the mortar paste by the clay bricks [27].

3.1.6 Porosity ($\emptyset$)

The physical change due to the firing of clay bricks in kilns depends on various factors that further influence porosity ($\emptyset$). Porosity is defined as the ratio of the volume of cracks and pores (void spaces) and the total volume of the specimen. In regards to clay bricks, porosity ($\emptyset$) is a dominant variable as it influences properties like clay brick quality, durability, and strength[3]. The observed average porosity ($\emptyset$)of the NSCB of heritage monuments in Punjab is 20.48 %. The highest is 28.64 % for the 18thcentury monument “Tomb of Ustad” (TOU) located in Fatehgarh Sahib district, Punjab and the lowest is 11.40 % for the 17th century monument MS [Mughal Serai] located in Ludhiana district, Punjab.

Table 3. Average values of physical properties of heritage Nanakshahi clay bricks (NSCB).

Site Code	District	Bulk density (ρ_b) (kg/m^3)	Apparent density (ρ_0) (kg/m^3)	Specific gravity (γ)	Void ratio (e) (%)	Water absorption (w_a) (%)	Initial rate of absorption (IRA) (g/cm^2/min)	Porosity ($\emptyset$) (%)
(TOU)	Fatehgarh Sahib	1514	1511	2.31	33.58	14.57	29.80	28.64
(TOS)	FatehgarhSahib	1640	1638	2.27	30.30	13.29	47.32	23.12
(DTH)	FatehgarhSahib	2447	2444	2.16	22.37	10.26	26.31	20.98
(MSQ)	FatehgarhSahib	1874	1867	2.13	20.22	9.47	30.27	17.84
(TORS)	FatehgarhSahib	1661	1659	2.27	31.07	13.64	54.15	23.70
(QMP)	Patiala	1544	1544	2.20	20.61	9.34	29.78	17.08
(AKB-FS)	FatehgarhSahib	2099	2096	2.09	17.34	8.29	22.88	17.61
(NQ)	Patiala	1778	1775	2.31	30.16	12.98	54.39	21.68
(QR)	Malerkotla	1726	1724	2.31	28.11	12.17	60.20	22.45
(SMS)	Malerkotla	1732	1728	2.29	33.42	14.56	52.47	21.81
(DSK)	Ludhiana	1994	1990	2.30	31.84	13.81	22.23	23.61
(MS)	Ludhiana	1948	1944	2.19	25.27	11.23	38.12	11.40
(AKB-RS)	FatehgarhSahib	1707	1703	1.99	26.10	8.60	17.49	15.09
Average of all sites		**1820**	**1817**	**2.22**	**26.95**	**11.70**	**37.34**	**20.38**
Standard deviation		**254.81**	**254.30**	**0.10**	**5.41**	**2.29**	**14.55**	**4.46**

Table 4. Comparison of physical properties of Nanakshahi (NSCB), newly prepared (NPCB) and contemporary clay bricks (CCB).

District location of clay bricks	Clay brick type	Average bulk density (ρ_b) (kg/m^3)	Average apparent density (ρ_0) (kg/m^3)	Average specific gravity (γ)	Average void ratio (e) (%)	Average water absorption (w_a) (%)	Average initial rate of absorption (IRA) (g/cm^2/min)	Average porosity ($\emptyset$) (%)
Fatehgarh Sahib	NSCB	1848.85	1845.42	2.17	25.85	11.16	32.60	20.99
	NPCB	1870	1866.57	2.39	36.19	11.50	42.70	21.60
	CCB	1225	1217	1.61	33.85	11.30	60.89	19.10
Patiala	NSCB	1661	1659.5	2.25	25.38	11.16	42.08	19.38
	NPCB	1890	1888.5	2.45	17.88	11.96	43.60	22.63
	CCB	1250	1237	1.63	21.63	11.56	60.32	18.06
Malerkotla	NSCB	1729	1726	2.30	30.76	13.36	56.33	22.13
	NPCB	2000	1997	2.55	20.23	10.56	28.83	21.32
	CCB	1443	1432	1.72	25.14	12.87	91.05	20.22
Ludhiana	NSCB	1971	1967	2.24	28.55	12.52	30.17	17.50
	NPCB	1811	1807	2.32	28.87	11.18	38.68	20.39
	CCB	1485	1474	1.66	28.32	13.48	81.85	22.45
Standard deviation	**NSCB**	**136.58**	**135.60**	**0.05**	**2.50**	**1.08**	**11.86**	**2.01**
	NPCB	**78.97**	**79.34**	**0.09**	**8.38**	**0.58**	**6.76**	**0.92**
	CCB	**132.28**	**131.85**	**0.04**	**5.18**	**1.04**	**15.38**	**1.88**

In comparison with heritage bricks from Punjab regions, the CCB and NPCB have an average porosity ($\emptyset$) of 18.26% and 21.48 %, respectively. On reviewing the literature, various studies have shown that the durability of bricks is strongly affected by the proportion of large pores with an increase in firing temperature, which reduces the connectivity of the pores and diminishes small pores [28, 29]. A higher porosity($\emptyset$) observed for ancient clay bricks, ranging between 15 - 40 % [30] and 15 - 35 % was reported from Byzantine Empire [31]. The porosity ($\emptyset$) of the red and beige-colored clay bricks' of the mosque in Istanbul, Turkey lies between 26 - 30 % and 40 - 55 % [32]. The clay brick porosity ($\emptyset$) from the 9th to the 10th and from the 12th to the 18th centuries varied between 21 - 35 % and 12 - 43 %, respectively, with a mean value of 18 % [3, 33].

3.2. Chemical compositions

XRF analysis of the collected heritage NSCB revealed that greater contents of silica, alumina, iron, calcium, dipotassium oxide and magnesia were determined. Other minerals such as chlorine, zirconium, oxides of disodium, phosphorus, manganese, barium, chromium, zinc, rubidium, strontium, nickel, copper, titanium dioxide, trioxides of sulphur and dichromium, were found in lesser proportions. Lead monoxide and gallium oxide can also be seen in small traces. Taking into account the above findings, it can also be concluded that the presence of silica in higher concentrations indicates that the heritage monuments of the southeastern Punjab were constructed using high-quality NSCB [34]. The NSCB's binding strength comes from minerals such as iron and magnesia [23]. Calcium silicate, which provides temperature resistance and structure stability, plays a major role in the conservation state of clay bricks [35]. Since the NSCB contains titanium dioxide, it has been observed that its resistance to spalling and cracking is enhanced due to its ability to resist high temperatures [26], further influencing the mechanical and physical properties of clay bricks [12].

Table 5. Chemical composition and molecular structure of NSCB.

Sample location	Minerals (%)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	Others
Fatehgarh Sahib	59.26	16.85	6.62	2.42	4.10	2.75	8
Patiala	66.27	15.31	5.82	4.23	3.02	2.09	2.56
Malerkotla	64.12	13.51	5.44	6.89	2.94	2.17	4.93
Ludhiana	64.82	16.60	7.01	2.56	3.80	2.29	2.92

In an effort to identify the chemical composition of the collected NSCBs, X-Ray fluorescence (XRF) analysis was performed. The NSCBs were found to contain greater quantities of SiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O and MgO during XRF analysis; other minerals such as Na_2O, CL, SO_3, TiO_2, P_2O_5, MnO, BaO, Cr_2O_3, ZrO_2, V_2O_5, ZnO, Rb_2O, SrO, NiO, $CaSiO_3$, CuO were found in smaller proportions, meanwhile Y_2O_3, PbO, Ga_2O_3, Nb_2O_5, As_2O_3 were also found in small amounts (Table 5) [9].

3.3. Mechanical properties

The clay brick mechanical property is the most influential and relevant parameter for determining the structural behavior of heritage monuments. The heritage NSCB, CCB and NPCB with similar elemental composition and dimensions were subjected to the compressive load for determination of mechanical property, particularly uniaxial compressive strength (f_m). In this study, the uniaxial compressive strength of the heritage NSCB is compared with that of the CCB and NPCB (Table 6).

According to the results of mechanical property tests, the average uniaxial compressive strength of the heritage NSCB and NPCB (having similar compositions and dimensions as the heritage NSCB) in the southeastern Punjab region is almost identical at 50.5 MPa and 53.26 MPa, respectively. With a mean of 21.90 MPa, the value for the CCB (modern clay bricks collected from selected districts' kilns) is almost 50 % less than that of the NSCB and NPCB. There is a variance in clay brick thickness and pore density, which accounts for this difference [36]. In order to determine the compressive strength of the brick in relation to the brick thickness, normalization is performed. In terms of compressive strength, there is a direct relationship between the mortar, masonry walls and unit thickness [37]. Clay brick masonry is highly influenced by specimen thickness [9]. The NPCBs are found to be reasonably suitable for the repair and replacement of heritage monuments in terms of their mechanical properties, as the mean values of their uniaxial compressive strength are fairly similar.

3.3.1. Uniaxial compressive strength of heritage Nanakshahi clay bricks (NSCB)

In the present study, the collected unadorned Nanakshahi clay bricks with slightly uneven surfaces were capped prior to uni-axial compression strength (f_m) testing under a load cell. The uniaxial compressive strength (f_m) of the heritage NSCB from the 14^{th} to 19^{th} century monuments ranges from 21.64 MPa to 151.8 MPa, with 50.5 MPa as its mean value. From the literature review, the compressive strength(f_m) of ancient clay bricks from heritage Portuguese monuments built between the 12^{th} and 19^{th} centuries widely varies from 6.7 MPa to 21.8 MPa with an average strength of 11.5 Mpa [38] and the red and brown-colored clay bricks of the ancient heritage structure in Italy ranges between 8 MPa - 12.4 MPa and 9.4 MPa - 25.43 Mpa

[21]. The uniaxial compressive strength (f_m) of clay bricks in Lucknow city, which lies within northern India, ranges between 12.9 MPa and 24.5 MPa, with an average value of 17.4 Mpa [26].

3.3.2. Uniaxial compressive strength of contemporary clay bricks (CCB)

The 1stclass hand-molded contemporary clay bricks collected from four different brick kilns located in the selected districts of Punjab were tested and analyzed in uniaxial compression [11]. The average compressive strength (f_m) of the CCB in the southeastern Punjab region ranges between 20.56 MPa and 22.62 MPa, with a mean of 21.90 MPa that is comparable with the contemporary clay bricks of northern India [26].

3.3.3. Uniaxial compressive strength (UCS) of newly prepared clay bricks (NPCB)

Table 6. Comparison of a average uniaxial compression strengths "UCS" (σ) of heritage NSCB, NPCB and CCB.

Site No.	District	Average UCS (f_m)of loosely collected clay bricks (MPa) & sample location	Average UCS (f_m) of loosely collected heritage Nanakshahi clay bricks (NSCB) (MPa)	Average UCS (f_m) of newly prepared clay bricks (NPCB) with similar composition (MPa)	Average UCS (f_m) of contemporary clay bricks (CCB) of four districts of Punjab region (MPa)
1	Fatehgarh Sahib	36.34 (Tomb of Ustaad Syed khan)	41.27	44.33	22.62
2		35.97 (Tomb of Shagird)			
3		24.35 (Diwan Todar Mal Haveli)			
4		104.115 (Mosque Sadhna Qasai)			
5		31.79 (Tomb of Rauza Sharif)			
7		29 (Aamkhas Bagh)			
13		27.33 (Aamkhas Bagh_Rear Side)			
6	Patiala	151.8 (Quila Mubarak)	94.28	57.83	22.05
8		36.76 (Nabha Qilla)			
9	Malerkotla	30.71 (Qilla Rehmatgarh)	35.91	70.77	22.38
10		41.11 (Sheesh mehal)			
11	Ludhiana	21.64 (Diwan Lashkari Kotta)	30.57	40.11	20.56
12		39.51 (Mughal Sarai)			
Average of all sites			**50.5**	**53.26**	**21.90**

Based upon the XRF analysis, the newly prepared clay bricks with similar dimensions and chemical compositions were prepared. The NPCBs were tested for uniaxial compression using a universal testing machine's load cell under controlled conditions. The uniaxial compression strength (f_m) of the NPCB lies between 40.11 MPa and 70.77 MPa. The average uniaxial compression strength of the NPCB in the selected Punjab districts as obtained is 53.26 MPa.

4. CONCLUSIONS

The study aims to experimentally analyze and present a property comparison of the heritage NSCB, NPCB and CCB of the southeastern districts of Punjab with the following observations:

1. The heritage NSCBs have similar average bulk density (ρ_b), apparent density (ρ_0), water absorption (w_a) and porosity ($\emptyset$) as compared to the 21st century NPCBs. The similarity may be attributed to the use of clay from the same geographical region for manufacturing NPCBs.
2. The heritage NSCB initial rate of absorption (IRA) is lower than that of the NPCB which may be due to the discrepancy between conventional and unconventional workmanship.
3. The NSCBs from the 14th to 19th centuries have similar average uniaxial compression strengths (f_m) as compared to the NPCB which broadly justifies the constituents as an outcome of the study.
4. Both the NSCB and NPCB have average uniaxial compression strength (f_m) twice as strong as the CCBs. This may be attributed to the thickness of the specimen; an important outcome of the study signifying the aspect ratio of the bricks contributing highly to the compression strength of heritage monuments.
5. This study confirms that in the chemical elemental composition of the heritage NSCB samples, a large proportion is filler elements like silica (SiO_2) and binding elements such as aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), potassium oxide (K_2O), and magnesium oxide (MgO).

CRediT authorship contribution statement. Guljit Singh: Investigation, Writing - Original Draft, Visualization. Anshu Tomar: Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision. Varinder Singh Kanwar: Validation, Resources, Writing - Review & Editing, Supervision.

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