International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I12P129

Volume 72 Issue 12, 349-359, December 2024

Original Article

Strength Characterization of Historical Masonry Building in Kathmandu Valley, Nepal

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Received: 17 June 2024 Revised: 02 October 2024 Accepted: 29 October 2024 Published: 25 December 2024

Abstract *- This study aims to characterize the strength of historical brick masonry buildings constructed with mud mortar by conducting a series of in-situ tests. Many of these structures are located in seismic regions and have suffered significant earthquake damage. Masonry buildings are inherently vulnerable to seismic events, varying performance from building to building. Since evaluating the mechanical properties of every masonry structure is often impractical, this study focuses on generalizing the mechanical properties of historical buildings with mud mortar. Seven different historical buildings were selected for the study. In-situ tests, including compression tests, shear tests, and pocket penetrometer tests, were conducted to determine the mechanical properties of the masonry. In contrast, brick tests were carried out in the laboratory to assess the compressive strength of the bricks. The results indicated that the compressive strength of brick masonry in mud mortar was 2.85 N/mm², while the shear strength was 0.06 N/mm². The mud mortar and bricks compressive strengths were 1.33 N/mm² and 9.09 N/mm², respectively, and modulus of elasticity was estimated at 1570.1 N/mm². This study provides valuable mechanical property data for historical brick masonry buildings with mud mortar, offering a reference for future evaluations of similar structures where such properties are unknown, especially in seismic vulnerability.*

Keywords *- Compressive strength, Shear strength, Brick strength, Pocket penetrometer test, Masonry Buildings.*

1. Introduction

A great earthquake occurred on April 25, with a magnitude of 7.8, hit Barpark, Gorkha (Pandit et al., 2016; USGS, 2015), and struck Kathmandu, Nepal. Referring to the report of the National Planning Commission (PDNA Vol B, 2015), many structures were influenced by the earthquake and its sequences. These structures include the United Nations Educational, Scientific and Cultural Organization (UNESCO) sites in the Kathmandu Valley. Several seismic activities (earthquakes) have been recorded to affect several masonry structures in seismic areas. Some of the reported earthquakes, including Iran (2003), Pakistan (2005), Peru (2007), Sikkim/Nepal fringe (2011), and Gorkha (2015), have destroyed lives and infrastructure (Chaulagain & Gautam, 2015; PDNA Vol B, 2015). For instance, the 2011 quake recorded in Sikkim/Nepal affected 14544 houses, among which 6435 were damaged; the Gorkha quake 2015 in Nepal killed roughly 9,000 individuals and damaged 474025 low-strength masonry buildings and 173867 were partially damaged (PDNA Vol B, 2015). Most of the historical and masonry building (URM) structures were significantly damaged due to the Gorkha Earthquake 2015. Ensuring building safety and integrity requires strict adherence to the Nepal National Building Code (NNBC) and compliance with approved architectural and engineering designs (Shrestha & Giri, 2023). A comprehensive building survey assesses current parameters to predict structures and elements' future reliability and safety (Shesterikova et al., 2023). Masonry's key advantage lies in its material strength, which, with proper selection, can last for centuries with minimal maintenance. While masonry excels in sustaining compressive loads, its strain and shear capacity are comparatively low. The material's non-uniformity and directional dependency complicate generalising its mechanical properties under shear and compression. Walls and piers are essential components of masonry structures, and shear mechanisms are imperative, especially when these walls encounter in-plane lateral stresses. This makes understanding masonry's shear behavior essential for ensuring structural integrity under such conditions. The values that determine the strength of masonry have no direct and accurate implication on the failure materials regarding the actual stresses; however, the characterized value is evaluated depending on the cross-sectional area of individual structural components. Some researchers (Mishra et al., 2018; H. R. Parajuli, 2012; R. R. Parajuli et al., 2020) worked to determine the mechanical properties of Nepalese historic masonry buildings. Preserving heritage buildings during design analysis is challenging, ensuring they remain intact without damaging their original state during construction (Triastuti et al., 2023), which leads to the requirement of characterized mechanical properties. After the damage to many historical masonry buildings due to the Gorkha earthquake (2015), analysis was difficult due to uncertainty regarding the property of masonry buildings. Researchers Mishara and Parajuli have studied masonry's mechanical properties to understand it better. Their research comprises laboratory tests of the masonry. Their test sample accomplishes the new material rather than the existing elements. This study fills this gap by conducting tests at different selected sites. Due to the variation in mechanical properties, this study aims to evaluate the representative compressive strength, shear strength, brick compressive strength, and mortar strength verified through various series of tests such as In-situ compressive and shear test, brick compression test, and pocket penetrometer test.

1.1. Limitation and Scope

The scope of this investigation is restricted by the variability in the mechanical characteristics of the masonry and the availability of equipment, contingent upon resources and site accessibility:

- The building is selected where access is allowed.
- The study is focused on the test conducted at the site.
- The brick compression test is conducted in the laboratory.
- Compressive, shear, and pocket penetrometer tests are selected as in-situ tests.
- The study is concluded based on test results obtained for selected seven buildings.
- The study does not anticipate seismic resistance and retrofit design.
- The study did not encompass cultural and religious criteria.
- A simple average is calculated to evaluate the characterized strength of the study.

2. Sample for Study

2.1. Building Under Study

Table 1. List of sampled building

Sampled Number	Sampled Historical Buildings
1	Kumari Chhe
2	Patan Darbar
3	Gopichandra Maha Bihar
4	Napichandra Mahabihar
5	Keshar Mahal
6	Babar Mahal
7	Bagh Darbar
8	Juddha Fire Brigade

Most historical buildings have been renovated and reconstructed to preserve historical and archaeological value worldwide. Historical buildings in Nepal have also been renovated and reconstructed to conserve historical and archaeological value. Seven selected sample buildings in Kathmandu district are listed in Table 1 for the study.

2.1.1. Kumari Chhe (Kumari Residence)

The building exists at 27°42'13.752"N, 85°18'24.0156" E Kumari Chhe (Kumari Residence) is a brick masonry building in mud mortar built in traditional Newar architecture and technology in 1757 by King Jaya Prakash Malla shown in Figure 1. The building was built as a residential building for the living goddess Kumari, who is believed to be the reincarnation of Goddess Talaju. Kumari Ghar was improvised and renovated in 1966 AD.

2.1.2. Patan Darbar (Patan Palace)

The building is located at 27°40'35.69"N, 85°18'51.01"E. Patan Darbar (Palace) complex construction project was executed in the 17th century by King Siddhi Narasimha Malla and was continued by his son Srinivasa Malla. Patan Palace complex was built in a different period's traditional Newari architecture and technology. The palace complex consists mainly of three courtyards: SundariChowk, MulChowk, and Keshav Narayan Chowk, constructed in 1647, 1666, and 1734, respectively.

Fig. 1 Kumari chhe

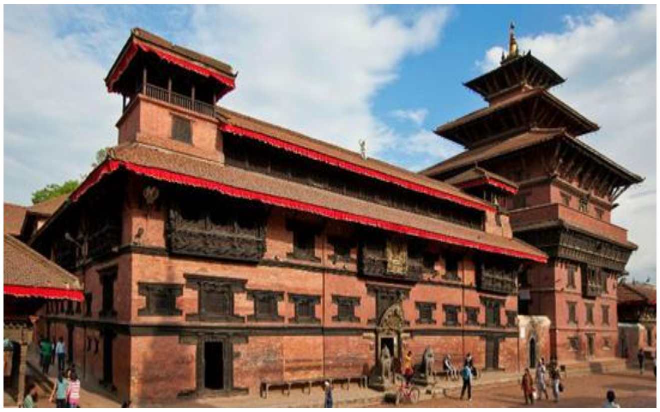

Fig. 2 Patan darbar

2.1.3. Gopichandra Mahabihar and Napichandra Mahabihar

Gopichandra MahaBihar and Napichandra Mahabihar are located at 27°40'40" N, 85°19'30"E, and 27°40'40.43"N, 85°19'29.98"E, respectively shown in Figures 3(a) and 3(b). These Mahabihars are one of the iconic Buddhist holy places in Lalitpur. It is believed that the original Gopichandra and Napichandra Mahabihar were constructed in the same year of the 18th century. Present-day Mahabihar was renovated after heavy damage in 1975.

2.1.4. Keshar Mahal (Keshar Palace)

The building is situated at 27°42'55.93"N, 85°18'50.78"E. Kehsar Mahal is an essential historical building in Nepal. It was built in 1895 by Chandra Shumsher Jang Bahadur Rana for his son Keshar Shumsher Jang Bahadur Rana. Like Babar Mahal, this complex was built in neoclassical architecture, as shown in Figure 4. The complex was offered to the Government of Nepal in 1964 AD after the death of Keshar Shumsher. Before the Gorkha Earthquake in 2015, the complex was consolidated by the Ministry of Education and Keshar Library.

(a)

(b)

Fig. 3 Sample mahabihar; (a) Gopichandra mahabihar, (b) Napichandra mahabihar

Fig. 4 Keshar mahal

2.1.5. Babarmahal (Babar Palace)

The building exists at 27°41'34.58"N, 85°19'28.04"E. In the beginning, the Palace complex was under Jung Bahadur Rana's Thapathali Durbar (Thapathali Darbar); later, it was isolated, demolished, and rebuilt by Chandra Shumsher Jang Bahadur Rana in 1910 and was affected by the 1934 Bihar-Nepal earthquake (Rana, 1935).

The Baharmahal Palace complex is in an inalienable Neoclassical style built in brick masonry with mud mortar and five courtyards, as shown in Figure 5. After the fall of the Rana regime, Baber Shamsher Jang Bahadur Rana occupied and controlled Babar Mahal and later sold it to the Government of Nepal

2.1.6. Bagh Darbar

The building is located at 27°41'55"N, 85°18'43"E; Bagh Durbar is one of the essential historical buildings in Nepal. Amar Singh Thapa built Bagh Darbar Palace, and later, a new palace was built in neoclassical architecture, shown in Figure 6 by Bhimsen Thapa in 1805 AD. Later, the palace was seized by the Government of Nepal in 1837 AD. Comple was highly affected by the Gorkha Earthquake in 2015. Currently, the building is occupied by Kathmandu Metropolitan Office.

Fig. 5 Babar mahal

Fig. 6 Bagh Darbar

Fig. 7 Juddha fire brigade

2.1.7. Juddha Fire Brigade

The building is located at 27°42'55.93"N, 85°18'50.78"E, Nepal's first fire brigade. In the name of Juddha Shumsher Jang Bahadur Rana, a mud mortar brick masonry building was constructed in 1937 AD, reflecting Rana Architectusnip, shown in Figure 7. Before the Gorkha Earthquake 2015, a 39.01 m x 9.8 m dimension building was used as a fire brigade building.

3. Materials and Methods

This study assessed seven brick masonry buildings constructed with mud mortar, as indicated in Table 1, and conducted in-situ tests to evaluate their characterized strength. The study assesses historical masonry structures' compressive and shear strength, particularly in earthquake-affected regions. According to the Department of Archeology (DOA, 2016), the earthquake impacted 745 monuments in 20 districts, with 193 collapsing completely. This study aims to delineate the mechanical characteristics of selected buildings by in-situ testing.

3.1. Mechanical Properties

It is complicated to simplify the mechanical characteristics of masonry structures due to non-homogeneity and anisotropy properties. As the shear property of masonry structures is a dominating character in lateral loads, walls and piers are considered major structural. A series of tests are performed in seven different sampled structures to recommend representative mechanical properties of historic masonry buildings.

3.1.1. Compressive Strength

Compressive strength is crucial for evaluating and designing masonry elements. Since compression testing is not always feasible, researchers have developed empirical expressions to relate the compressive strengths of masonry units and mortar for more practical assessments in masonry structures.

$$f_m' = K f_b'^{\alpha} x f_i'^{\beta} \qquad (1)$$

In Eurocode 6, 2005, constants K, α\, and β are used, where f_b, f_i, and f_m represent the compressive strengths of brick units, mortar, and masonry, respectively. The code suggests a range for K based on brick unit properties and the bond arrangement between brick and mortar, with α=0.7 and β=0.3. Since β is less than α, masonry compressive strength (f_m) is influenced more by brick strength (f_b) than by mortar strength (f_i). These constants are used to determine the 5% lower characteristic compressive strength. Bennett et al., 1997, through regression analysis of experimental data with cement mortars, suggested a simple linear relationship, estimating that the compressive strength of masonry is 0.3 times the compressive strength of bricks, providing a practical estimate of masonry strength based on brick properties.

Dayaratnam, 1987 proposed equal weights for α and β, with a K value 0.275. Kaushik et al., 2007, through experiments and regression analysis, suggested values of K=0.63, α=0.49, and β=0.32. Gumaste et al. 2006, in their study involving bricks tested with various mortars, derived values of K=0.317, α=0.866, and β=0.134, comparing their results with Hendry and Malek, 1986 who obtained K=0.317, α=0.531, and β=0.208 for cement-lime mortars.

IS 1893 (IS 1893:2016, 2016) also recommends an empirical equation for unreinforced masonry infill prisms, with constants K=0.433, α=0.64, and β=0.36, to estimate the permissible compressive stress. Development and experimentation on the reliability of compressive strength tests started with Maier et al. 1983, who adopted the technique for brick masonry. Other relevant contributions are made by Abrams & Epperson, 1989 and Noland et al. 1990. In-situ compressive test was attempted to correlate with the laboratory compressive test provided by Gregorczyk & Lourenço 2000, and Dalla 2012.

3.1.2. Modulus of Elasticity

The Modulus of Elasticity of masonry is determined from the linear portion of the stress-strain curve. It typically ranges from 5% to 33% of the ultimate compressive strength, reflecting the material's ability to deform under stress. As per Eurocode 6 (Eurocode 6, 2005), the empirical equation for masonry elastic modulus can be presented as follows:

$$E_m = K f_m^{'} \tag{2}$$

Where K is constant in the empirical expression for the Modulus of Elasticity, the K value for masonry's modulus of elasticity (E_m) varies by recommendation. The MSJC code (MSJC, 2002) suggests Em = $700f'_m$ for modern masonry, while FEMA 306, 2000. recommends Em = 550f’m for existing masonry. The Canadian masonry code (CSA, 2005) proposes a slightly higher value, Em = 850f’m, for modern masonry. Likewise, the Indian Standard code (IS 1893:2016, 2016) recommends that Em equals 550fm. This study adheres to the Indian Standard parameter to identify the modulus of elasticity of mud mortar masonry historical buildings.

3.1.3. Shear Strength

Eurocode 6, 2005 stipulates that the shear strength of masonry is determined by adding the shear strength at zero compressive stress with 40% of the design compressive stress perpendicular to the shear. Tomaževič, 2009 demonstrated that, for any mortar type, the typical masonry shear strength represented by Equation 3, provided both head joints and bed joint are adequately filled with mortar, ensuring the integrity of the masonry under shear forces.

$$f_{vo} = f_{vko} + 0.4\sigma_d \tag{3}$$

Where f_{vko} represents characteristic shear strength (initial) at zero compression and σ_d represents design compressive strength in MPa for a selected wall section. FEMA 274, 1997. stipulates that the vertical compressive stress must be subtracted from this number to ascertain the bed joint shear stress at the testing site, supposing a friction coefficient 1.0. Because expected wall shear strength data will be used, the 50th percentile value (V_{to}), utilized as an index value in Equation 4:

$$V_{to} = \frac{V_{test}}{A_b} - P_{D+L} \tag{4}$$

FEMA 310, 1998 has recommended that the shear wall strength (Va) be calculated with Equation 5.

$$V_a = 0.67 v_{me} D t \tag{5}$$

Where D, t, and v_{me} represent the width, the thickness of the wall, and expected masonry shear strength, respectively;

Shear strength (V_{me}) is calculated by the Equation 6;

$$v_{me} = \frac{0.75(0.75 v_{te} + \frac{P_{CE}}{A_n}}{1.5} \tag{6}$$

Where vte, PCE, and An are the average bed-joint shear strength, the compressive force due to self-weight acting on the wall of the pier under consideration, and the net area of the section, respectively.

Nevertheless, Indian Standard code IS 1905:1987 (IS 1905 : 1987, 1995) suggests permissible shear stress with the empirical formula considering the factor of compressive strength of wall or pier acted upon self-load also with an empirical constant value of 0.1, which is represented as in Equation 7,

$$f_s = 0.1 + \frac{f_d}{6} \tag{7}$$

Where f_d represents compressive stress due to dead load.

3.2. Test Procedure

3.2.1. In-situ Shear test

In-situ shear strength of clay masonry units and their mortar joints is evaluated using a non-destructive testing method. As shown in Figure 8, a hydraulic jack is placed in the position of the removed masonry unit. The mortar on the subsequent brick at the side is removed to isolate the test unit, allowing for horizontal displacement upon applying force.

The test unit slides when applying force parallel to the wall's length. Force measured at the masonry unit's initial movement is then divided by its total contact area to determine the shear strength. The non-destructive test assesses the in-situ shear strength between a clay masonry unit and the mortar joints above and below it.

3.2.2. In-situ Compressive test

The non-destructive test for masonry walls measures the in-situ compressive strength. Two points in the wall are identified to determine the vertical deflection. A hydraulic jack is positioned vertically in a space created by the extraction of a masonry unit. The hydraulic jack is pressurized to the deflected wall until its original position is reached, estimated by the two points marked before the removal of the masonry unit, as shown in Figure 9. The stress evaluated to regain the original position of the deformed masonry wall is estimated as developed compressive strength at the time of test observed on the test panel of the building.

Fig. 8 In-situ shear test

Fig. 9 In-situ Compression test

3.2.3. Mortar Strength test

For the masonry compression test, the pocket penetrometer test is used for this study. A pocket penetrometer instrument is a small-sized device that fits in a pocket, and it is a spring-operated device used to evaluate the compressive strength of mortar. This device contains a pushed piston, and the maximum reading is recorded to evaluate mortar compressive strength. Moisture affects the pocket penetrometer test result; hence, accurate results can be obtained by limiting the moisture (18-25%) (Yasun, 2018). Mortar strength at the site is determined by performing the pocket penetrometer test on mortar joints at different building locations. A similar test was performed by Dawid Latka (Łatka & Matysek, 2020) in the historical building, and the test result displayed the result of mortar strength to be 1.4 to 2.9 MPa. The selection of points for the pocket penetrometer test is fixed on the dry surface of the mortar. Test using a pocket penetrometer is conducted by applying pressure at the back of the device on a clear mortar surface, as shown in Figure 10. The reading obtained on the shaft after applying pressure is considered the reading of the pocked penetrometer test. This test is not conducted in the Juddha fire brigade office.

Fig. 10 Pocket penetrometer test

Fig. 11 Brick compression test

3.2.4. Brick Compression test

After cleaning the selected sample brick extracted from the site, unevenness is removed. The frog portion and voids are filled with 1C:1S (cement and coarse sand of grade 3mm or down) mortar after 24 hours of immersion of brick in water and drain out excess water at room temperature. The jute bag is wrapped in sampled brick for 24 hours. Following the process, the brick is tested after 3 days, as shown in Figure 11.

4. Results and Discussion

The mechanical characteristics of masonry buildings may appear inconsistent, making it challenging to determine their characteristics. Various tests on buildings constructed with mud mortar are conducted to establish representative mechanical values. The outcomes depend on the specific sampled buildings, as the number of tests can vary due to limitations in sample collection and accessibility. This heterogeneity emphasizes the significance of using specialized testing methods to measure these masonry buildings' mechanical properties appropriately.

4.1. Compressive Strength Test

An in-situ test was performed to acquire the mechanical parameters of selected brick masonry buildings. Shear test and compressive test were conducted at different locations of the building. Using the FEMA 274 (FEMA 274, 1997) guidelines. The numbers of test locations and sample collections are different due to restrictions for sample collection and accessibility. A vertical void in the wall is made to install the hydraulic jack to evaluate the compression strength. The orientation of the hydraulic jack is kept perpendicular separately to determine compression tests. Tested results for an individual building are also shown in Table 2. At least three minimum number of tests were performed in each building.

Table 2. In-situ test (Compressive Strength)

Sno.	Historical Buildings	Number of tests	In-Situ test	
			Compressive strength	
			Value	Average
			N/mm^2	N/mm^2
1	Kumari Chhe	3	3.27, 3.33, 3.33	3.31
2	Patan Darbar	3	3.21, 3.27, 3.39	3.29
3	Gopichandra Mahabihar	3	3.21,3.23, 3.27	3.24
4	Napichandra Mahabihar	3	3.2, 3.3, 3.33	3.28
5	Keshar Mahal	12	3.33, 3.39, 3.52, 3.39, 3.39, 3.46, 3.58, 3.33, 3.46, 3.52, 3.39, 3.33	3.42
6	Babar Mahal	14	3.27, 3.39, 3.39, 3.46, 3.33, 3.33, 3.46, 3.39, 3.39, 3.46, 3.33, 3.39, 3.33, 3.39	3.38
7	Bagh Darbar	3	3.27, 3.34, 3.33	3.31
8	Juddha Fire Brigade	3	3.21, 3.39, 3.26	3.29
Average			**3.31**	
Corrected Compressive Strength			**2.85**	

Table 3. Compressive stress by other references

Sno.	References	Formula	f'm (MPa)
1	Eurocode 6	$f'_m = K f_b^{\alpha}$ x f_j^{β}	2.55
2	Bennett et al.	$f'_m = K f_b$	2.73
3	Dayaratnam	$f'_m = K f_b^{\alpha}$ x f_j^{β}	0.95
4	MSJC	$f'_m = (400+0.25f_b)/145$	2.77
5	Kaushik et al	$f'_m = K f_b^{\alpha}$ x f_j^{β}	2.04
6	Gumaste and Venkataram Reddy	$f'_m = K f_b^{\alpha}$ x f_j^{β}	2.23
7	Hendry and Malek	$f'_m = K f_b^{\alpha}$ x f_j^{β}	1.08
8	IS 1893:2016	$f'_m = K f_b\alpha$ x f_j^{β}	1.97

Table 4. In-situ test (Shear Strength)

Sno.	Historical Buildings	Number of tests	In-Situ test	
			Shear Strength	
			Value	Average
			N/mm^2	N/mm^2
1	Kumari Chhe	3	0.04, 0.07, 0.06	0.06
2	Patan Darbar	3	0.03, 0.04, 0.05	0.04
3	Gopichandra Maha Bihar	3	0.02, 0.09, 0.08	0.06
4	Napichandra Mahabihar	3	0.08, 0.8, 0.1	0.09
5	Keshar Mahal	12	0.04, 0.04, 0.06, 0.07, 0.06, 0.01, 0.06, 0.07, 0.07, 0.08, 0.07, 0.08	0.06
6	Babar Mahal	14	0.02, 0.06, 0.06, 0.05, 0.04, 0.03, 0.03, 0.04, 0.06, 0.03, 0.03, 0.07, 0.03, 0.03	0.04
7	Bagh Darbar	6	0.1, 0.1, 0.08, 0.09, 0.06, 0.08	0.09
8	Juddha Fire Brigade	4	0.19, 0.043, 0.031, 0.019	0.07
Characterized Shear Strength			**0.06**	

The compressive strength of brick masonry overall varies from 3.21 Mpa to 3.58 Mpa. It various 3.27 MPa to 3.33 MPa in Kumari Chhe, 3.21 MPa to 3.39 MPa in Patan Darbar, 3.21 MPa to 3.27 MPa in Gopichandra Mahabihar, 3.2 MPa to 3.33 MPa in Napichandra Mahabihar, 3.33 MPa to 3.58 MPa in Keshar Mahal, 3.33 MPa to 3.49 MPa in Babar Mahal, 3.27 MPa to 3.33 MPa in Bagh Durbar, 3.21 MPa to 3.39 MPa in Juddha Fire Brigade as represented in Table 2. The average compressive strength of brick masonry for each building is calculated as shown in Table 2, and the overall average value is obtained to be 3.32 Mpa.

The height of the wall above the testing machine is 1.5 m, and the thickness of the wall on average is 900mm in the considered building since the ratio of height to least lateral dimension designated the aspect ratio is 1.5 (ASTM C1314-14, 2016) and the correction factor is 0.86. hence, the corrected compressive stress of masonry is 2.85 MPa. Compressive strength obtained by the formula proposed by other references is expressed in Table 3. The output obtained closely matches the formula Bennett et al. and MSJC gave. This verifies that the compressive strength obtained from the in-situ test is essentially applicable.

4.2. Shear Strength Test

As with the Compressive Strength Test, the number of tests depends on the site. A horizontal void in the wall is made to install the hydraulic jack horizontally to evaluate the shear in masonry. The orientation of the hydraulic jack is kept parallel to the brick alignment, and pressure is applied. The mortar of the adjacent brick is removed, allowing horizontal displacement. The applied pressure and horizontal displacement were recorded to determine compression and shear tests. Mortar of adjacent brick Test results for an individual building are also shown in Table 4.

The average shear strength for each studied building varies from 0.04 to 0.07. It varies from 0.04 MPa to 0.07 MPa in Kumari Chhe, 0.03 MPa to 0.05 MPa in Patan Darbar, 0.02 MPa to 0.08 MPa in Gopichandra Mahabihar, 0.08 MPa to 0.1 MPa in Napichandra Mahabihar, 0.01 MPa to 0.08 MPa in Keshar Mahal, 0.02 MPa to 0.07 MPa in Babar Mahal, 0.08 MPa to 0.1 MPa in Bagh Durbar, 0.02 MPa to 0.04 MPa in Juddha Fire Brigade as represented in Table 4, from the data characterized shear strength is evaluated by averaging the average shear strength obtained from individual buildings to be as 0.06 MPa which is indicated in Table 4.

R. R. Parajuli et al., 2020 has reported characterized shear strength as 0.024 MPa teste in the Shingadarbar site, whereas Adhikari et al., 2019 reported shear strength as 0.08 MPa in his case study for Bagh Durbar which is very close finding in this study

4.3. Brick Compression Test

A brick compression test was performed using CTM with the sample obtained from the site. The number of samples for the test is different due to the authority's permission. The average strength is obtained from the individual building, and the characterized compressive strength of brick is estimated to be 9.09 MPa, as shown in Table 5, obtained by averaging the average of the individual building. The outcome from the compression test on brick is recorded, and the average value is determined for individual buildings under study. The average brick strength in compression varies from 4.5 MPa to 10.18 MPa. It various 8.32 MPa to 9.29 MPa in Kumari Chhe, 8.14 MPa to 10.5 MPa in Patan Darbar, 8.1 MPa to 9.5 MPa in Gopichandra Mahabihar, 8.5 MPa to 9.1 MPa in Napichandra Mahabihar, 7.95 MPa to 10.81 MPa in Keshar Mahal, 8.14 MPa to 9.08 MPa in Babar Mahal, 1.14 MPa to 6.63 MPa in Bagh Durbar, 9.46 MPa to 11.28 MPa in Juddha Fire Brigade as represented in Table 5. The characterized compressive strength of brick is evaluated by averaging the average compression strength obtained from the selected building. The evaluated characterized compressive strength of the brick is 9.09 MPa, as illustrated in Table 5. The compressive strength of brick reported by H. R. Parajuli, 2012 is 11.03 MPa in his case study of the Patan area, whereas R. R. Parajuli et al., 2020 reported brick compressive strength up to 7.64 MPa and Adhikari et al., 2019 in his case study of Bagh Durbar reported as 6.6 Mpa. The close output in a similar case study building demonstrates that the evaluated strength is realistic.

Table 5. Brick compression test

Sno.	**Historical Buildings**	**Number of tests**	**In-Situ test**	
			Compressive Strength	
			Value	**Average**
			N/mm^2	**N/mm^2**
1	Kumari Chhe	5	8.32, 9.08, 8.92, 9.29, 9.01	8.924
2	Patan Darbar	15	8.14, 8.5, 10.1, 9.1, 9.5, 905, 8.8, 10.5, 9.1, 9.2, 8.9, 8.4, 9.09, 9.3, 9.11	9.12
3	Gopichandra Maha Bihar	3	8.1, 9.3, 9.5	8.97
4	Napichandra Mahabihar	3	8.5, 9.1, 9.08	8.89
5	Keshar Mahal	24	7.95, 8.14, 9.51, 10.81, 9.29, 8.46, 8.26, 10.47, 9.51, 8.67, 8.46, 9.08, 9.51, 9.08, 9.49, 9.08,9.08, 8.56, 8.65, 8.7, 9.27, 9.29, 8.43, 9.7	9.06
6	Babar Mahal	14	8.32, 8.36, 8.14, 8.7, 9.08, 8.7, 8.56, 8.49, 8.7, 8.32, 8.14, 8.87, 8.45, 8.29	8.51
7	Bagh Darbar	3	6.63, 1.14, 5.3	4.5
8	Juddha Fire Brigade	5	9.64, 10.37, 9.46, 11.28, 10.18	10.18
Characterized Brick Compressive Strength			**9.09**	

Table 6. Pocket Penetrometer test

Sno.	**Historical Buildings**	**Test Number**	**In-Situ test**	
			Compressive Strength	
			Value	**Average**
			N/mm^2	**N/mm^2**
1	Kumari Chhe	15	1.37, 1.47, 1.27, 0.98, 1.16, 1.06, 1.76, 1.01, 1.45, 1.96, 1.72, 1.02, 1.62, 1.36, 1.37	1.372

2	Patan Darbar	15	1.27, 1.47, 1.18, 1.79, 1.03, 1.28, 1.37, 1.97, 1.85, 0.98, 0.99, 1.12, 1.03, 1.21, 1.16	1.31
3	Gopichandra Maha Bihar	5	1.18, 1.27, 1.37, 1.37, 1.33 , 1.21	1.272
4	Napichandra Mahabihar	5	1.37, 1.27, 1.16, 1.21, 1.32	1.266
5	Keshar Mahal	72	1.27: 7 no’s 1.37: 26 no’s 1.47: 28 no’s 1.57: 10 no’s 1.67: 1 no’s	1.431
6	Babar Mahal	15	1.47, 1.37, 1.47, 1.27, 1.37, 1.18, 1.37, 1.37, 1.27, 1.27, 1.57, 1.37, 1.18, 1.27, 1.35	1.343
7	Bagh Darbar	11	0.1, 0.12, 0.32, 0.3, 0.19, 0.11, 0.12, 0.19, 0.21, 0.19, 0.14	0.18
Characterized mortar compressive Strength			**1.33**	

4.4. Pocket Penetrometer Test

A portable spring-operated device known as a pocket penetrometer is used to evaluate the compressive strength of mortar at the site. Reading is recorded after pushing the piston into the mortar at several numbers of points for the selected seven buildings, as shown in Table 6. The strength of mud mortar captured using a pocket penetrometer is averaged for each building.

For different building under study mortar strength various as 0.98 MPa to 1.96 MPa in Kumari Chhe, 0.98 MPa to 1.97 MPa in Patan Darbar, 1.18 MPa to 1.37 MPa in Gopichandra Mahabihar, 1.16 MPa to 1.37 MPa in Napichandra Mahabihar, 1.27 MPa to 1.67 MPa in Keshar Mahal, 1.18 MPa to 1.57 MPa in Babar Mahal, 0.1 MPa to 0.32 MPa in Bagh Durbar, as represented in Table 6.

The average data obtained from each building is further averaged to establish the characterized compressive strength of mortar. The average mortar strength in compression varies from 0.18 MPa to 1.43 MPa. As the average data acquired in Bagh Darbar is very low and then other tested values in other buildings, the test result from Bagh Darbar is excluded. Hence, as recorded, the characterized compressive strength is 1.33 MPa, as shown in Table 6. H. R. Parajuli, 2012 reported mud mortar compressive strength of 1.58 MPa in his study, which is fairly close to the result in this study.

5. Conclusion

The structural properties of the mud mortar masonry utilized in heritage constructions have been better understood by the experimental study conducted on historical buildings in Kathmandu, Nepal. The mud mortar masonry is evaluated with a characterized shear strength of 0.06 N/mm² and a characterized compressive strength of 2.85 N/mm². Furthermore, the characterized compressive strength of brick and mortar was estimated as 9.09 N/mm² and 1.33 N/mm², respectively. Similarly, the modulus of elasticity of the existing historical masonry wall is 1570.1 N/mm2. Only a few historical buildings are considered in this study depending on the allowable access to the building by the concerned authority; hence, a similar study can be performed with more buildings, including districts other than Kathmandu. The equipment used for the study is not sophisticated and readily available in Kathmandu. Nevertheless, this study does not include the damage assessment or retrofit and restoration process regarding the preservation of the building. However, to preserve the historic buildings in Kathmandu, conservation strategies, structural conservation, and retrofitting efforts that utilize FEM modeling might be based on the characterized data gathered from the tests conducted in this study. To ensure the durability and resilience of these structures against future damage, it is imperative to create customized interventions that improve the shear resistance and general stability of these structures through analytical modeling using the result of the study, unless site-specific data is unviable.

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