

Article

Investigating the Compressive Strength of Clay Brick Masonry: A Case Study of Nangarhar, Afghanistan

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Abstract: In Afghanistan, masonry structures using burnt clay bricks have long been used for public and private buildings. However, still, there is no standard for masonry structural design based on local material properties. This study investigated the compressive strength of clay brick masonry prisms in Nangarhar, Afghanistan, through experimental testing and finite element modeling (FEM). Three brick classes, with compressive strengths between 8 and 14 MPa, were used to construct prism specimens. The research aimed to propose specific values for masonry compressive strength using local materials and examine the effects of brick strength (f_b), mortar strength (f_j), joint thickness (t_j), and slenderness ratio (h/t) on masonry compressive strength (f_m). Test results showed f_m values of 17.2 MPa for first-class, 10.0 MPa for second-class, and 7.6 MPa for third-class brick masonry, indicating the influence of the brick's quality. Key findings showed that an increase in f_b causes an equal increase in f_m , a 5% increase in f_j leads to a 1% increase in f_m , a 5 mm increase in t_j gives an 8% f_m increase, and a 5.5% increase in h/t results in a 1% decrease in f_m . The research provides valuable information for evaluating the compressive strength of masonry structures based on the quality of local materials, which can be used to revise Chapter 7 of the *Afghanistan Building Code, 2012*.

Keywords: Afghanistan; clay brick masonry; masonry compressive strength; compression tests; finite element model

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1. Introduction

The use of clay bricks in construction is a long-standing practice in Afghanistan. Typically, these bricks are produced locally by hand in warm environments, blending natural materials such as clay and sand, hardened by exposure to sunlight, and burnt in traditional kilns. Brick production remains prevalent in the construction industry of developing countries globally. Since 2001, nearly all new school buildings in Afghanistan, and many modern residential buildings, have been built using a masonry construction system, mostly using either masonry-infilled reinforced concrete (RC) or confined masonry buildings, designed and constructed without a recognized building and construction code [1].

Afghanistan lies in a region of high seismic activity, with many strong earthquakes causing fatalities in Afghanistan's history [2]. In October 2023, an earthquake with a magnitude of 6.3 at a depth of 9 km struck the Herat province of western Afghanistan. At the time, the United States Geological Survey (USGS) reported that the population in that region resided within structures vulnerable to earthquake shaking, including adobe blocks and unreinforced brick buildings of mud and timber [3]. This powerful earthquake caused extensive damage to existing structures, resulting in losses estimated at USD 100 million, with over 2000 fatalities and thousands more people injured or displaced. Another similarly severe earthquake occurred in June 2022 in Paktia, an eastern province of

Afghanistan, with a magnitude of 6.2 at a depth of 4 km. This event resulted in approximately 1200 fatalities and widespread destruction of homes and infrastructure. Figures 1 and 2 show that these recent seismic activities damaged even the few masonry-infilled RC Masjid buildings in Herat and Paktia. These buildings, used as village learning centers, saw the tragic deaths of tens of children during the earthquakes. These events underscore the urgent need for improved seismic resilience and the emergency evaluation of existing buildings in Afghanistan.



Figure 1. Masonry-infilled RC Masjid building damaged in the Herat Earthquake, 2023 (taken by <https://www.alamy.com/>, accessed on 15 September 2024).



Figure 2. Masonry-infilled RC Gian Masjid building damaged in the Paktia Earthquake, 2022.

The shear strength of masonry walls is crucial in evaluating masonry structures' seismic or wind load capacity. Several pieces of research indicate that compressive strength is a key parameter in determining lateral strength. For instance, Alwashali [4] proposed Equation (1) to calculate the shear strength (Q_u) of masonry infill walls.

$$Q_u = 0.04 f_m t L \gamma \quad (1)$$

Here, f_m is masonry compressive strength, and t and L are wall thickness and length $\gamma = 1$ when $\beta \leq 0.7$, $\gamma = 1.45 \beta$ when $0.7 < \beta < 1.3$, and $\gamma = 1.9$ when $\beta \geq 1.3$, where β is the ratio of expected bare frame lateral strength to the expected infill masonry strength [4]. Thus, to use this or similar equations, it is essential to know the precise value of the compressive strength of masonry based on local material quality.

The *Afghanistan Building Code* (ABC) [5], which was published in 2012, adopted the masonry standards from the *International Building Code* (IBC)[6] without localization and any adjustments for materials, seismicity, or geotechnical conditions. Despite the widespread use of masonry in traditional construction in Afghanistan and its combined use with concrete in modern construction, there is a lack of data and experimental research on the properties of masonry materials used in the region. For instance, in Chapter 7 of the ABC, which details masonry structure design and analysis, brick unit compressive strength (f_b) is listed as ranging between 12 and 80 MPa, giving predicted clay brick

masonry compressive strength (f_m) values ranging between 7 and 28 MPa. However, on-site observations demonstrate that masonry often has f_b and f_m values other than those listed in the ABC. As a result, calculating the shear strength Q_u of masonry structures may present uncertainties.

A study by Ali et al. [7] in Peshawar, Pakistan—near Nangarhar, Afghanistan—examined the compressive strength of locally produced burnt clay bricks. According to the study, the compressive strength of Class 1 bricks ranges from 11 to 24 MPa, that of Class 2 bricks ranges from 7 to 13 MPa, and Class 3 bricks have a compressive strength between 5 and 8 MPa, indicating clearly which is the strength difference between each quality class. However, even though burnt clay bricks are classified into three classes in Afghanistan, no experimental research provides information about their compressive strength. Therefore, this knowledge gap impedes the accurate prediction of the compressive strength of masonry structures, which is fundamental for the seismic capacity evaluation of new or existing structures.

Also, understanding the factors that most influence the compressive strength of clay brick masonry is crucial to understanding the behavior of masonry. Numerous studies have investigated the compressive strength of masonry structures, offering valuable insight into the various facets of masonry behavior under compressive forces. Foytong et al. [8], Murthi et al. [9] and Cavalaro et al. [10] comprehensively studied the effect of brick units on masonry compressive strength, revealing that the brick unit strength is the most influential factor. The Foytong et al. study demonstrated this relationship; the masonry prisms with the highest f_b (29.4 MPa) also had the strongest average f_m of 10.8 MPa, while prisms made of brick units with the lowest f_b (2.6 MPa) resulted in prisms with the weakest f_m (3.55 MPa).

The nuanced impact of mortar properties and joint thickness (t_j) on the compressive strength of masonry walls has also been explored recently, encompassing both experimental and numerical analyses [10,11]. Liang et al. [12] compared the failure models of masonry columns constructed with various types of mortar. They suggested that the primary cause of failure is tensile splitting within the masonry column. This splitting propagated through the mortar joint, with failure occurring in the vertical contact between the brick unit and mortar. These findings suggest that the interaction between mortar and brick units is one of the critical factors leading to masonry failure—meanwhile, Zengin et al. [13] underscored the crucial role of mortar thickness in determining structural performance by comparing masonry with 10 mm, 20 mm, and 30 mm mortar thicknesses. The highest lateral load was observed for specimens with a 20 mm mortar joint. On the other hand, specimens with 10 mm and 30 mm joint thicknesses showed lower lateral loads but very close values among them. The larger scale of damage was observed for joint mortar of 10 mm, indicating a lack of cohesion between mortar and bricks.

Additionally, recent studies have addressed the significance of geometric considerations in masonry design. Khan et al. [14] and Abasi et al. [15] have devoted their efforts to understanding the behavior of masonry structures under various slenderness ratios (the wall height to thickness ratio, h/t). Khan et al. proposed an empirical Equation (2) that considers h/t and the width-to-thickness ratio (L/t), in addition to brick compressive strength (f_b) and the compressive strength of the mortar (f_j), recognizing the importance of these parameters in predicting masonry compressive strength.

$$f_m = f_b \left(\frac{4 + 0.1 f_j}{1.5 \frac{L}{t} + 5 \frac{h}{t}} \right) \quad (2)$$

Compressive strain behavior—material deformation under stress—is equally critical as compressive strength for evaluating how structures respond to static and seismic loads. Studies show that stress–strain behavior under compression is crucial for determining the modulus of elasticity [16], which is essential to evaluating the ductility and the stiffness and understanding the failure patterns of those structures under seismic loads [17–20].

Despite these findings, the *Afghanistan Building Code* does not consider any difference in the compressive strength of bricks based on their quality, mortar strength, mortar joint width, and stress–strain relationship evaluations, which creates a gap in ensuring structural safety and resilience, particularly for regions prone to seismic activity [5].

Therefore, due to the crucial role and heterogeneous characteristics of materials used in masonry construction, which vary from site to site [21], this paper investigates the compressive strength of clay brick masonry prisms. An experimental program was conducted in Nangarhar, an eastern province of Afghanistan, and complemented by finite element model (FEM) analysis. The primary objective was to propose specific values for the compressive strength of masonry (f_m) structures constructed with local materials. Four categories of masonry prism specimens were prepared to evaluate the effects of various parameters on the compressive strength of the prisms, including brick compressive strength f_b (Category 1), mortar compressive strength f_i (Category 2), mortar joint width t_j (Category 3), and slenderness ratio h/t (Category 4). A better understanding of the compressive strength of masonry, by prism models, and its influencing factors will facilitate a more accurate prediction of the structural performance of both new and existing masonry constructions in Nangarhar, which can be extended later to other regions of the country.

2. Experimental Testing Program

This research was conducted using local materials from Nangarhar, an eastern province of Afghanistan, well-known for its clay brick production. The masonry materials were tested at the Hask Engineering Materials Laboratory in Nangarhar province in collaboration with Nangarhar University. The location of the research area is illustrated in Figure 3.

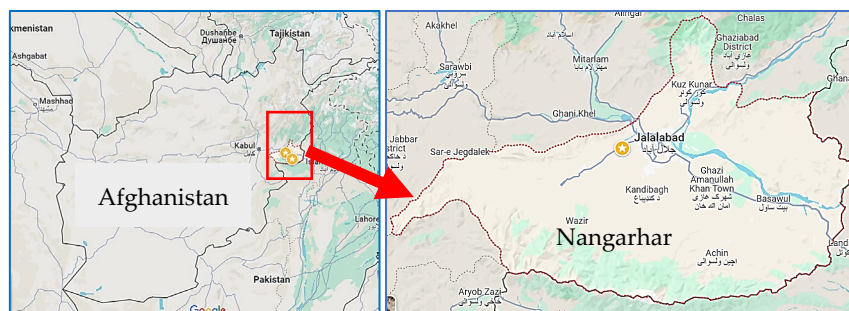


Figure 3. Location of research area (taken from Google maps).

The experimental investigation involved compressive strength tests on clay brick units, joint mortar-made cubes, and masonry prisms of varying categories. A graphical representation of the test specimens is shown in Figure 4.

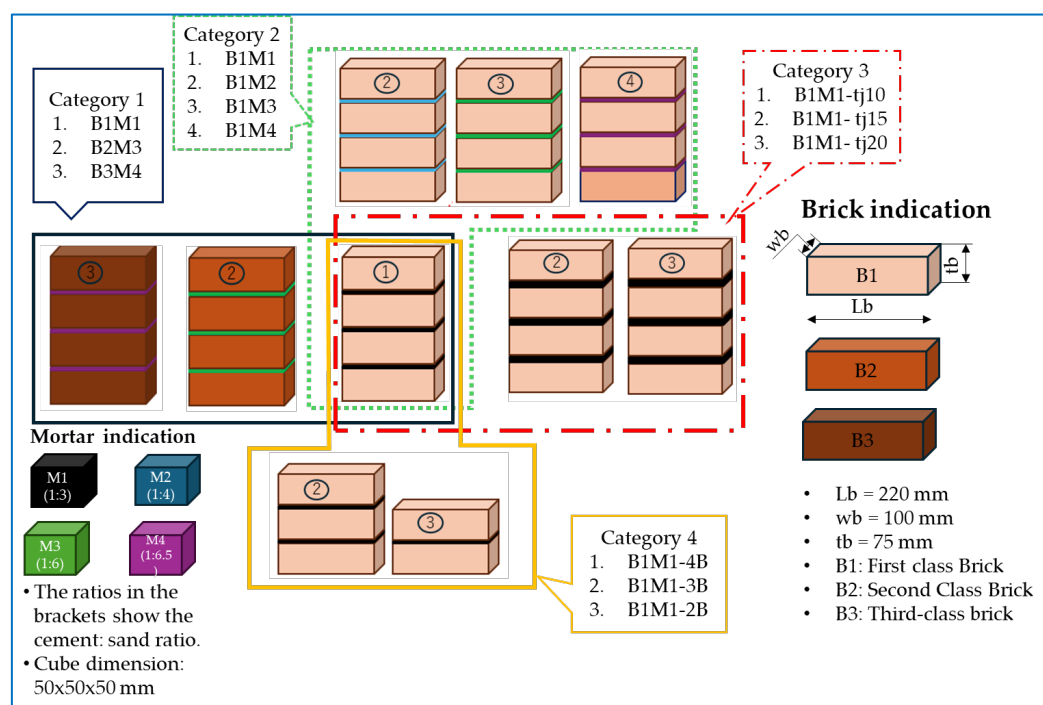


Figure 4. Graphical representation of the specimens used in experimental tests.

In Afghanistan, like Pakistan and other surrounding regions, burnt brick units are classified into three classes [7]. The first-class bricks, named B1, are of a standard size and shape and are well burnt, with a uniform color (yellow or red) and a regular texture. They have a water absorption capacity of less than 10%, an expected compressive strength of 14.0 MPa or higher, with no efflorescence, emit a metallic sound when struck, and are hard enough to resist fingernail impressions and are mainly used for structural resistant elements.

The second-class bricks, named B2, also have a standard size, regular shape, uniform yellow or red color, with some minimal efflorescence, are well burnt (slightly over-burnt is acceptable), emit a metallic sound when struck, and resist fingernail impressions. The B2 bricks have a 10–15% water absorption capacity and an expected compressive strength between 7 and 14 MPa. They are typically used for one-story buildings and temporary sheds.

In contrast, third-class bricks (B3) are irregular in shape and size and burnt (slightly over-burnt is acceptable), with a soft, light red color and non-uniform texture. B3 bricks have a 15–20% water absorption capacity, a compressive strength between 3.5 and 7 MPa, and extensive efflorescence. They emit a dull sound when struck and leave fingernail impressions.

Four types of mortar, denoted M1, M2, M3, and M4, with differing cement-to-sand ratios, 1:3, 1:4, 1:6, and 1:6.5, respectively, were tested in this study. The ratios were chosen based on the local mortar mixtures commonly used.

For the experimental testing program, masonry prism specimens were constructed of either four, three, or two brick layers. The four categories of prism specimens designed for this study were as follows:

- **Category 1:** To assess the compressive strength of commonly used brick masonry in Nangarhar. Three different prism specimens were tested: B1M1, B2M3, and B3M4. The notations indicate the combination of brick-and-mortar types used to construct each prism specimen. All Category 1 prism specimens were constructed with four brick layers and 10 mm thick mortar joints, giving a slenderness ratio (h/t) of 3.3.
- **Category 2:** To examine the effect of mortar compressive strength on masonry compressive strength. The four mortar types (M1 to M4) were used to construct prism specimens with only B1 brick units. The Category 2 specimens, constructed with four brick layers and 10 mm thick mortar joints, are denoted B1M1 (same as Category 1), B1M2, B1M3, and B1M4.

- Category 3: To investigate the effect of mortar joint thickness (t_j) on compressive strength. The prism specimens were constructed using B1 bricks and M1 mortar, each made of four brick layers and three mortar layers of varying thicknesses of 10 mm, 15 mm, and 20 mm. The specimens are B1M1- t_j 10 (same as B1M1 of Category 1), B1M1- t_j 15, and B1M1- t_j 20, respectively.
- Category 4: To evaluate the impact of the slenderness ratio on compressive strength. Prism specimens were constructed with B1 bricks and M1 mortar, varying the number of bricklayers (four, three, and two layers). The specimens of this category are B1M1-4B (same as B1M1 of Category 1), B1M1-3B, and B1M1-2B, respectively.

Tables 1–3 summarize the dimensional details of the brick unit, mortar cube, and masonry prism test specimens.

Table 1. Dimension of the brick unit.

Length (mm)	Width (mm)	Height (mm)
220	100	75

Table 2. Mortar mix and dimension of mortar cube specimens.

Mortar Type	Cement–Sand Ratio	Water–Cement Ratio	Length (mm)	Width (mm)	Height (mm)
M1	1:3	0.58	50	50	50
M2	1:4	0.55			
M3	1:6	0.52			
M4	1:6.5	0.49			

Table 3. Masonry prism specimens' dimensions.

Symbol	Length (mm)	Width (mm)	Height (mm)	Mortar Thickness (mm)	Slenderness Ratio	
Category 1	B1M1	220	100	330	10	3.3
	B2M3					
	B3M4					
Category 2	B1M1	220	100	330	10	3.3
	B1M2					
	B1M3					
	B1M4					
Category 3	B1M1-tj10	220	100	330	10	3.3
	B1M1-tj15			345	15	3.5
	B1M1-tj20			360	20	3.6
Category 4	B1M1-4B	220	100	330	10	3.3
	B1M1-3B			245		2.5
	B1M1-2B			160		1.6

2.1. Preparation of Test Specimens

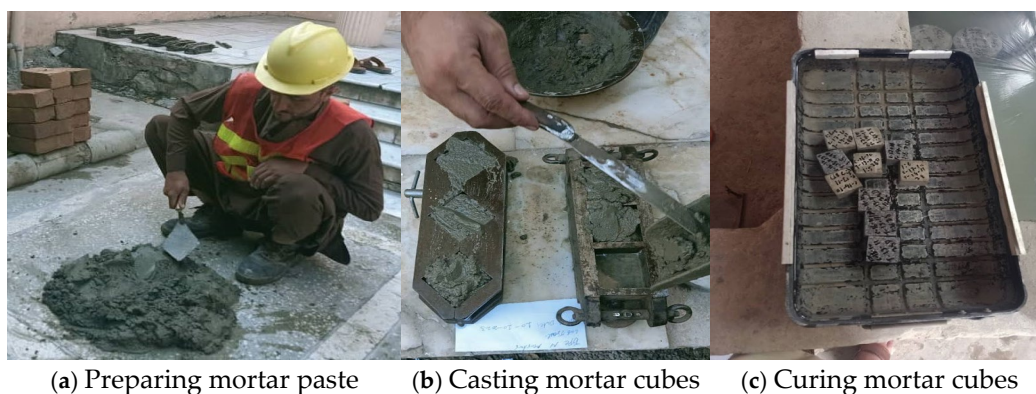
Three brick units (B1, B2, B3) with varying compressive strengths were sourced from Surkhroud Kiln of Nangarhar, Afghanistan. As shown in Figure 5, the bricks' dimensions, density, and water absorption were measured according to the ASTM-C62 standard [22]. Six specimens from each brick class were randomly chosen for physical measurements and brick compressive strength (f_b) test. Additionally, all brick units used in prism specimens' construction were submerged in water for 24 h before use to minimize their water absorption from the mortar during the hardening process.



(a) Weighing brick units (b) Soaking brick units (c) Brick dimension measurement

Figure 5. Brick preparation and measurement of physical properties.

Figure 6 shows the $50 \times 50 \times 50$ mm cube specimens of each mortar type (M1 to M4) prepared based on the ASTM C109 [23] Code for the mortar compressive strength tests. After the initial hardening process, all mortar cube specimens were submerged in a water tank at room temperature in preparation for testing.



(a) Preparing mortar paste (b) Casting mortar cubes (c) Curing mortar cubes

Figure 6. Mortar cube specimens' preparation.

A local expert mason prepared the prism specimens according to the experimental program outlined in Figure 4. As shown in Figure 7, the prism specimens were cured for 28 days in an open area and watered twice a day.



Figure 7. Masonry prism specimens during the curing stage.

2.2. Materials Compressive Tests

Compressive tests were conducted on six specimens of each brick unit and mortar cube type and three replicates of each prism specimen. All tests were performed using a Digital Compression Testing Machine (serial number 0592) with a loading capacity of 2000 KN, following ASTM E-4 [24] and ASTM E-74-04 [25] procedures. The load was applied

at a rate of 0.5 MPa/s, as recommended by the ASTM standards for masonry testing, to prevent shock loading and ensure uniform stress distribution across specimens. The peak compressive load of each specimen was recorded to ensure the results' accuracy and consistency.

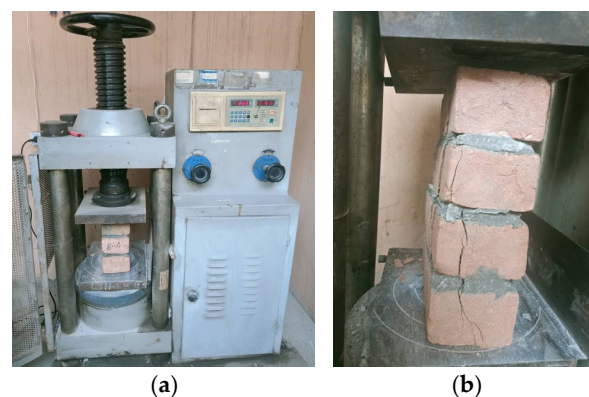
Figure 8a shows the brick unit's compressive tests. Figure 8b,c shows the mortar compressive strength tests conducted after the mortar cubes specimens had cured for 7 or 28 days, respectively.



(a) Brick unit testing (b) Mortar cube testing on the 7th day (c) Mortar cube testing on the 28th day

Figure 8. Compressive strength testing of masonry materials.

The prism specimens, shown in Figure 9, were tested after curing for 28 days when the final strength of the mortar joint was achieved.



(a) (b)

Figure 9. Compressive testing of masonry prism specimens.

3. Evaluation of the Stress–Strain Relationship by Finite Element Modelling

The testing device used for the experiment could not measure the strain deformation during the loading processes. To address this limitation, Finite Element Model (FEM) analysis was employed to simulate the stress–strain relationship of masonry prisms under compressive loading.

The various masonry prisms were modeled using FEM analysis to evaluate the influence of brick unit compressive strength (f_b), mortar compressive strength (f_j), mortar thickness (t_j), and the slenderness ratio (h/t) on masonry compressive behavior. Hence, FEM simulation and analysis were conducted using STKO software (Version 3.3.0) [26]. To examine the stress–strain behavior of masonry prisms under compression.

3.1. Geometry

The three-dimensional (3D) geometry of Category 1 to 4 masonry prisms was modeled using the dimensions indicated in Table 3. Figure 10a–c shows samples of four, three, and two brick layer prism specimens.

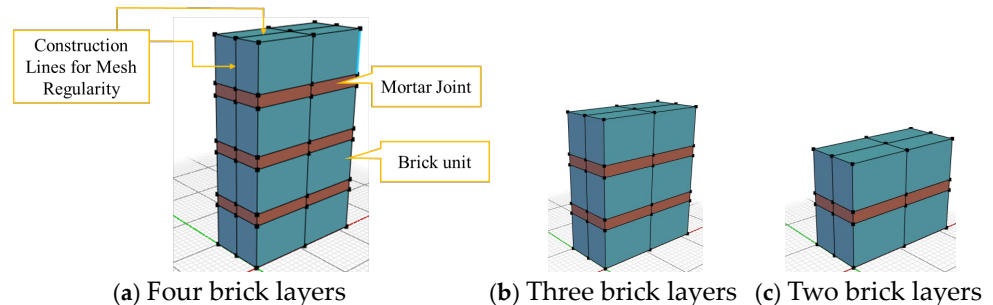


Figure 10. The 3D geometric finite element models of masonry prism specimens.

3.2. Element Type and Meshing

The bbarBrick [26] element type is applied for both brick unit and mortar joints. It is a specialized type of 3D brick element. It features a mixed formulation designed to address volumetric locking, which can occur when materials are nearly incompressible, such as under high pressure or constrained deformations. This element is an 8-node iso-parametric element (each corner node contributing degrees of freedom), which makes it suitable for simulating the behavior of solid materials under static or dynamic loads.

A linear tetrahedral mesh is selected to ensure a consistent mesh structure, utilizing 8-node iso-parametric elements for meshing the model. A uniform mesh size of 5 mm is applied to maintain resolution across the geometry.

3.3. Materials' Mechanical Properties

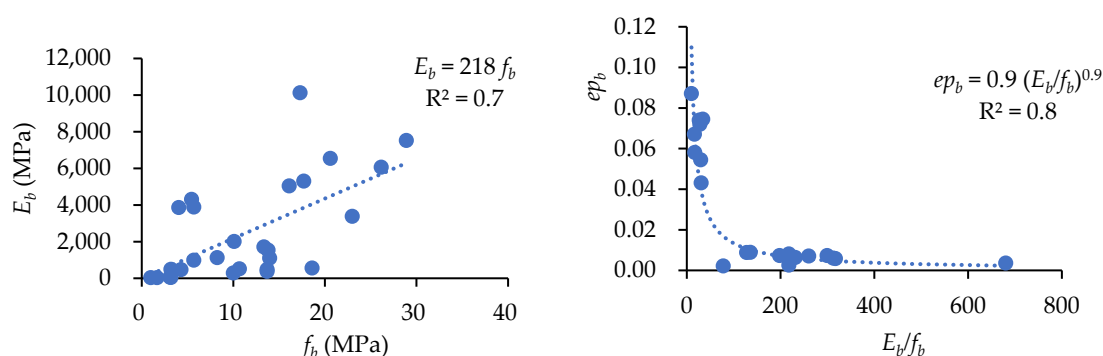
Two-dimensional continuous micro-models (2D-C) [27–30] of the brick units and mortar joints were used to accurately represent the physical dimensions and configurations of the experimental specimens. To simulate the mechanical properties of brick and mortar, the DamageTC3D model is used [31–33] and modeling of DamageTC3D includes:

1. Compressive properties: materials' peak compressive strength (f), elastic compressive strength (f_{c0}), residual compressive strength (f_{cr}), the strain at peak compressive strength (ep), and compressive fracture energy (G_c);
2. Tensile properties: materials' tensile strength (ft) and tensile fracture energy (G_t);
3. Elastic properties: materials' modulus of elasticity (E) and Poisson's ratio (ν);
4. Density (ρ).

The peak compressive strengths of brick units (f_b) obtained from the experimental tests carried out in this research were used for the modeling. The elastic (f_{c0-b}) and residual (f_{cr-b}) compressive strengths of the brick were considered to be 70% and 10% of the f_b , respectively [31]. The modulus of elasticity of the brick (E_b) and strain at the peak compressive strength of the brick (ep_b) are calculated by regression using the experimental data of clay brick units compressive test obtained from the literature, presented in Table 4. The regression expressions are illustrated in Figure 10. Figure 11a,b shows the relationship between E_b with f_b and ep_b with f_b , respectively. Additionally, the coefficient of determination (R^2) values for both models are 0.7 and 0.8, respectively, indicating the satisfactory fit of empirical equations derived by regression.

Table 4. Brick unit modulus of elasticity (E_b) and strain at peak compressive strength (ep_b) from compressive test experiments from the literature.

Specimen No	f_b (MPa)	E_b (MPa)	E_b/f_b	ep_b	References
10	18.6	554	30	0.0544	[16]
11	13.7	470	34	0.0744	
12	10.0	279	28	0.0719	
13	13.7	367	27	0.0739	
28	8.2	-	-	0.0025	[17]
1	17.7	5299	299	0.0072	[18]
2	16.1	5030	312	0.006	
3	28.9	7517	260	0.007	
4	20.6	6534	317	0.0057	
	10.1	2001	198	0.0072	[19]
	13.3	1705	128	0.0087	
	8.2	1116	135	0.0088	
5	26.2	6056	231	0.0063	[21]
27	13.8	1530	111	-	[29]
8	5.7	3878	680	0.0035	[34]
9	14.0	1090	78	0.0021	[35]
15	1.0	30	31	0.043	[36]
16	3.2	32	10	0.087	
17	1.7	27	16	0.067	
18	3.1	53	17	0.058	
19	10.7	509	48	-	[37]
20	4.3	467	109	-	
21	3.2	485	152	-	
22	5.7	976	171	-	[38]
23	23.0	3372	147	-	
24	4.1	3856	952	-	[39]
25	17.3	10,122	585	-	
26	5.5	4300	789	-	[40]
29	3.6	-	-	0.008	[41]

**Figure 11.** Mechanical characteristics of clay bricks: (a) Brick unit modulus of elasticity (E_b) vs compressive strength (f_b), (b) Brick unit strain (ep_b) vs modulus of elasticity (E_b).

The elastic (f_{c0-j}) and residual (f_{cr-j}) compressive strengths of mortar were calculated as 70% and 10%, respectively [31], of the peak compressive strengths of mortar (f_i) obtained from this research.

The mortar modulus of elasticity (E_j) and strain at the peak compressive strength of the mortar (ep_j) are calculated by regression using the experimental data of the mortar cube compressive test obtained from the literature, presented in Tables 5 and 6, respectively. The linear regression expressions are illustrated in Figure 12. Figure 12a,b shows the relationship between E_j with f_j and ep_j with f_j and water–cement ratio (W/C). The coefficient of determination (R^2) for the relationship between E_j and f_j is 0.5, indicating a moderate correlation between the experimental results and the predictive model. In contrast, the R^2 value for the relationship involving ep_j and f_j and the water–cement ratio (W/C) is 0.8, suggesting a high correlation between the experimental results and the predictive model.

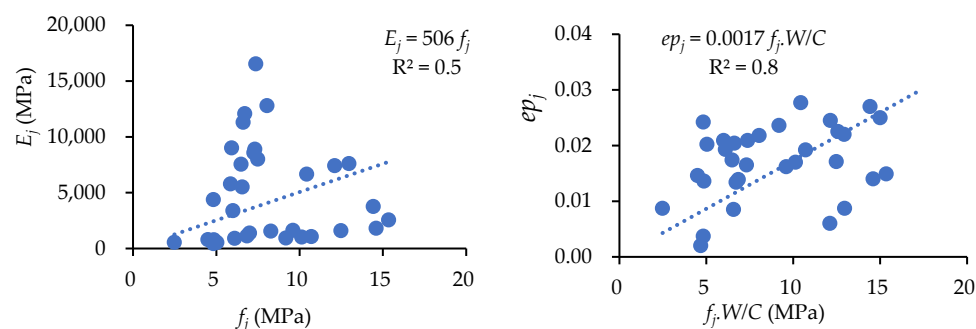
Table 5. Mortar modulus of elasticity (E_j) from compressive test experiments in the literature.

No.	W/C	C:S	f_j (MPa)	E_j (MPa)	Reference
10	0.5	1:3	30.7	2550	[16]
11	0.6	1:3	20.8	1587	
12	0.7	1:3	14.9	6651	
13	0.5	1:4	19.2	1619	
14	0.6	1:4	15.3	930	
15	0.7	1:4	15.3	1057	
16	0.5	1:5	12.2	902	
17	0.6	1:5	11.4	1116	
18	0.7	1:5	6.9	420	
19	0.5	1:6	9.0	785	
20	0.6	1:6	8.1	775	
21	0.7	1:6	7.2	518	[18]
8	0.7	1:3	20.6	3750	
9	0.8	1:6	3.1	545	[19]
25	0.7	1:3	20.9	1805	
26	0.8	1:5	12.7	1015	[29]
5	-	1:5	9.2	1545	
6	-	-	7.0	1365	[34]
1	0.6	1:3	21.6	7591	
2	0.7	1:4	17.3	7403	
3	0.7	1:6	6.9	4361	[37]
22	-	1:6	9.4	8000	
23	0.6	1:4	10.6	8997	
24	0.8	1:6	7.3	5766	[38]
4	1.1	1:6	6.6	8568	
7	1.2	1:5	5.0	3375	[39]
27	0.6	1:3	12.3	16,530	[42]
28	0.8	1:3	8.4	12,070	
29	1.0	1:3	7.3	8880	
30	0.4	1:3	16.5	11,300	
31	0.6	1:3	13.4	12,780	
32	0.8	1:3	8.1	7540	
33	1.26	1:8	5.2	5500	[43]

W/C, water to cement ratio; C:S, cement to sand ratio.

Table 6. Mortar compressive strain (ep_j) from compressive test experiments in the literature.

No.	W/C	C:S	f_j (MPa)	ep_j	Reference
27	0.8	1:6	3.1	0.009	[18]
28	0.7	1:3	20.6	0.027	
8	0.8	1:5	12.7	0.017	[19]
9	0.7	1:3	20.9	0.014	
30	0.7	1:6	6.9	0.004	[34]
31	0.7	1:4	17.3	0.006	
32	0.6	1:3	21.6	0.009	[16]
12	0.7	1:6	7.2	0.020	
13	0.6	1:6	8.1	0.014	
14	0.5	1:6	9.0	0.014	
15	0.7	1:5	6.9	0.024	
16	0.6	1:5	11.4	0.014	
17	0.5	1:5	12.2	0.019	
18	0.7	1:4	15.3	0.019	
19	0.6	1:4	15.3	0.024	
20	0.5	1:4	19.2	0.016	
21	0.7	1:3	14.9	0.028	
22	0.6	1:3	20.8	0.017	
23	0.5	1:3	30.7	0.015	
24	0.6	-	23.3	0.022	
25	0.6	-	19.4	0.0223	
26	0.7	1:2.7	16.4	0.025	
10	0.5	1:6	9.4	0.002	[37]
11	0.5	1:3	30.0	0.025	
29	1.2	1:5	5.0	0.021	[39]
1	0.6	1:3	12.3	0.021	[42]
2	1.3	1:8	5.2	0.009	
3	0.8	1:3	8.1	0.017	
4	0.6	1:3	13.4	0.022	
5	0.4	1:3	16.5	0.020	
6	1.0	1:3	7.3	0.017	
7	0.8	1:3	8.4	0.013	

**Figure 12.** Mechanical properties of mortar: (a) mortar modulus of elasticity (E_j) vs. compressive strength (f_j). (b) mortar strain (ep_j) vs. $f_j.W/C$.

The tensile strength (f_{tb}), the fracture energy under tension (G_{tb}), and compression (G_{cb}) of the brick unit were calculated using empirical Equations (3)–(5) [44] in contrast,

the tensile strength (f_{ij}), fracture energy under tension (G_{ij}), and fracture energy in compression (G_{cj}) of mortar were calculated using empirical Equations (6)–(8) [45].

$$f_{tb} = 0.087 f_b^{0.58} \quad (3)$$

$$G_{tb} = 0.025 (2 f_{tb})^{0.7} \quad (4)$$

$$G_{cb} = 15 + 0.43 f_b - 0.0036 f_b^2 \quad (5)$$

$$f_{ij} = 0.1 f_j \quad (6)$$

$$G_{ij} = 0.073 f_j^{0.18} \quad (7)$$

$$G_{cj} = 250 G_{ij} \quad (8)$$

The materials properties for brick units and mortar used in FEM analysis are summarized in Tables 7 and 8, respectively.

Table 7. Mechanical properties of brick units used in FEM.

Brick Class	Compression								Tension		Elasticity		Density
	f_b (MPa)	f_{c0-b} (MPa)	f_{cr-b} (MPa)	ep_b (mm/mm)	G_{cb} (N/mm)	c1	c2	c3	f_{tb} (MPa)	G_{tb} (N/mm)	E_b (MPa)	v_b	ρ_b (N/mm ³)
B1	14.2	7.1	1.4	0.0071	28.7	0.65	0.5	1.5	1.4	0.11	3100	0.15	1.7×10^{-5}
B2	10.6	5.3	1.1	0.0071	27.3	0.65	0.5	1.5	1.1	0.11	2310	0.15	1.6×10^{-5}
B3	8.2	4.1	0.8	0.0071	26.1	0.65	0.5	1.5	0.8	0.10	1790	0.15	1.6×10^{-5}

Table 8. Mechanical properties of mortar joint used in FEM.

Mortar type	Compression								Tension		Elasticity		Density
	f_j (MPa)	f_{c0-j} (MPa)	f_{cr-j} (MPa)	ep_j (mm/mm)	G_{cj} (N/mm)	c1	c2	c3	f_{tj} (MPa)	G_{tj} (N/mm)	E_j (MPa)	v_j	ρ_j (N/mm ³)
M1 (1:3)	22.1	11.1	2.2	0.0205	68.6	0.65	0.5	1.5	2.2	0.27	1,100,630	0.2	1.8×10^{-5}
M2 (1:5)	15.2	7.6	1.5	0.0134	47.2	0.65	0.5	1.5	1.5	0.19	76,090	0.2	1.8×10^{-5}
M3 (1:6)	8.6	4.3	0.9	0.0072	26.7	0.65	0.5	1.5	0.9	0.11	43,005	0.2	1.8×10^{-5}
M4 (1:8)	6.4	3.2	0.6	0.0050	19.9	0.65	0.5	1.5	0.6	0.08	32,004	0.2	1.8×10^{-5}

f : compressive peak strength, f_{c0} : compressive elastic strength, f_{cr} : compressive residual strength, ep : strain at peak compressive strength, G_c : compressive fracture energy, c1, c2, and c3: compressive law shape parameters considered as default, f_t : tensile strength, G_t : tensile fracture energy, E : modulus of elasticity, v : poisson's ratio, ρ : density. Note: The notation (b) indicates brick, and (j) indicates mortar properties.

3.4. Simulation of Loading Conditions:

The FEM models of masonry prisms were subjected to loading conditions representative of the experimental tests. A boundary condition was applied as fixed supports at the bottom, which were restrained translationally in all three directions. The top boundary condition was selected to allow compression load to be used in the vertical direction of the prisms. The load was applied as a uniform vertical displacement at the top of the prism to replicate the conditions of a compression test, following ASTM E-74 [25] guidelines to prevent shock loading. While nonlinear static analysis was performed to capture the stress–strain relationship of masonry under compressive loads.

4. Results

4.1. Bricks and Mortar Compressive Strength

Bricks are categorized into three classes based on their compressive strength, designated here as B1, B2, and B3. For each brick class, six specimens were tested (BS1 to BS6). The results of the average compressive strength for each class are presented in Table 9. The B1, B2, and B3 had an average compressive strength (f_b) of 14.2 MPa, 10.6 MPa, and 8.2 MPa, respectively, with a corresponding coefficient of variation (CoV) of 0.07, 0.1, and 0.21. The B1 and B2 average strength, with the 7% to 10% CoV, shows a slight variation in the results and high reliability in representing these brick classes. The B3 brick class showed the lowest f_b of 8.2 MPa and the highest CoV of 0.21, indicating more significant variability between the brick specimens tested and, therefore, lower reliability and accuracy of represented compressive strengths for this brick class.

As illustrated in Table 10, for the mortar compressive strength test, three specimens of each mortar type were tested after curing for 7 days (MS1-S3), and the remaining three specimens were tested after curing for 28 days (MS4-S6). The 7th-day compressive strengths of M1, M2, M3, and M4 mortar were 13.7, 11.8, 5.9, and 3.2 MPa, with coefficients of variation (CoV) of 0.13, 0.07, 0.27, and 0.13, respectively. The 28th-day compressive strengths were 22.1, 15.2, 8.6, and 6.4 MPa, with CoVs of 0.09, 0.15, 0.18, and 0.13, respectively. Based on the CoV, the results show low to moderate variability. Brick units and mortar cube failure are shown in Figure 13.

Table 9. Brick unit compressive strength.

Brick Class	Peak Compressive Load (kN)						Area (mm ²)	Average f_b (MPa)	CoV
	BS1	BS2	BS3	BS4	BS5	BS6			
B1	301.4	275.7	309.3	325.5	311.9	348.7	22,000	14.2	0.07
B2	235.1	215.4	204.2	241.8	238.8	268.7		10.6	0.10
B3	183.3	172.2	219.5	116.6	156.3	229.2		8.2	0.21

BS: brick specimen; f_b : brick compressive strength; CoV: coefficient of variation.

Table 10. Mortar compressive strength.

Mortar Type	Mixture C:S	Area (mm ²)	Peak Load at 7th Day (kN)			Average f_{j-7} (MPa)	CoV	Peak Load at 28th Day, (kN)			Average f_{j-28} (MPa)	CoV
			MS1	MS2	MS3			MS4	MS5	MS6		
M1	1:3	2500	34.2	39.7	28.5	13.7	0.13	50.3	53.6	61.8	22.1	0.09
M2	1:4		28.6	32.14	27.44	11.8	0.07	36.7	32.1	45.4	15.2	0.15
M3	1:6		15.2	9.54	19.24	5.9	0.27	16.1	23.3	25.1	8.6	0.18
M4	1:6.5		6.9	8.23	9.14	3.2	0.13	15.6	18.8	13.8	6.4	0.13

C:S: cement to sand ratio, MS: mortar specimen, CoV: coefficient of variation, f_{j-7} and f_{j-28} : mortar compressive strength after curing for 7 days and 28 days, respectively.



(a) Brick unit failure



(b) Mortar cube failure after curing for 28 days

Figure 13. Brick unit and mortar cube failure under uniaxial compressive load.

4.2. Compressive Strength Masonry Prism

Table 11 details the compressive strength test results of four categories of masonry prism specimens, with the results summarised in Figure 14. Also, Figure 15 shows the failure patterns of four, three, and two layers of prism specimens. Category 1, as shown in Figure 14a, compares three classes of brick-and-mortar combinations commonly used in the Nangarhar area. The results indicate that as the brick and mortar's compressive strengths decrease, the prism's overall compressive strength decreases significantly from 17.2 MPa to 7.6 MPa.

In contrast, in Category 2, shown in Figure 14b, where the brick unit compressive strength ($f_b = 14.2$ MPa, B1) is constant, a decrease in only mortar compressive strength (f_j), from 22.1 MPa to 6.4 MPa results in a smaller decrease in prism compressive strength, from 17.2 MPa to 12.3 MPa. Category 3 prism results, indicated in Figure 14c, show that increasing the mortar joint thickness (t_j) leads to increasing the prism's compressive strength.

Lastly, Category 4, indicated in Figure 14d, shows that as the slenderness ratio (h/t) decreases, the compressive strength of the prism increases. The CoV for each specimen ranges from 0.05 to 0.24 (5% to 24%) (see Table 11), with an average value of 0.09, indicating that the variation in the total results could be 9%.

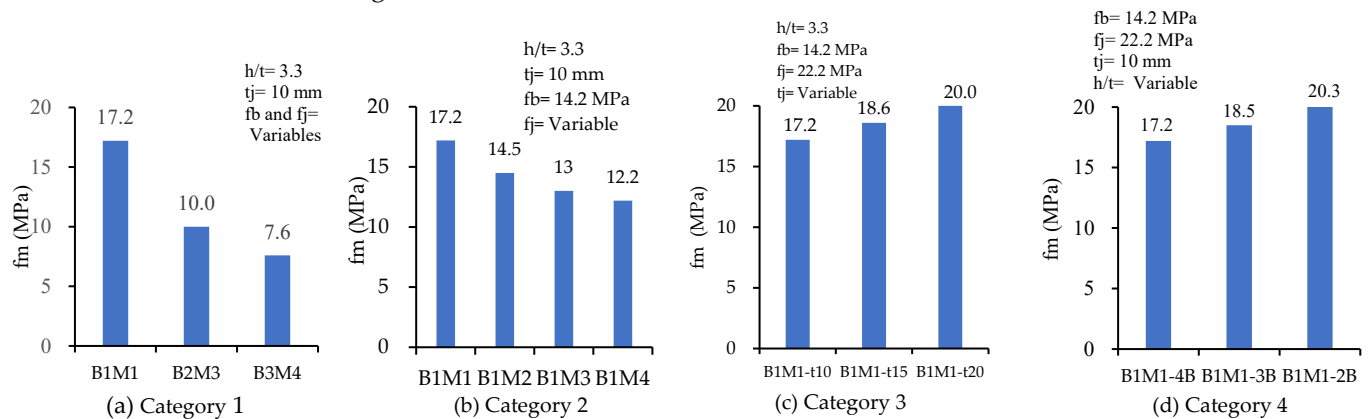


Figure 14. Masonry prism specimens' compressive strength.



(a) Four brick layers of prism (b) Three brick layers of prism (c) Two brick layers of prism

Figure 15. Failure pattern of prism specimens.

Table 11. Masonry prism specimens' compressive strength results.

Specimens		t_j (mm)	h/t	f_b (MPa)	f_i (MPa)	f_m (MPa)				CoV
						PS1	PS2	PS3	Average	
Category-1	B1M1	10	3.3	14.2	22.1	17.3	18.8	15.5	17.2	0.08
	B2M3					9.3	10.5	10.3	10.0	0.05
	B3M4					7.6	5.9	9.1	7.6	0.17
Category-2	B1M1	10	3.3	14.2	22.1	17.3	18.8	15.5	17.2	0.08
	B1M2					13.4	16.1	14.2	14.5	0.08
	B1M3					10.6	17.6	11.2	13.1	0.24
	B1M4					11.6	14.1	11.2	12.3	0.08
Category-3	B1M1- t_j 10	10	3.3	14.2	22.1	17.3	18.8	15.5	17.2	0.01
	B1M1- t_j 15	15	3.5			18.6	18.4	18.9	18.6	0.06
	B1M1- t_j 20	20	3.6			19.9	18.7	21.5	20.0	0.08
Category-4	B1M1-4B	10	3.3	14.2	22.1	17.3	18.8	15.5	17.2	0.04
	B1M1-3B		2.5			19.0	17.4	19.2	18.5	0.07
	B1M1-2B		1.6			21.4	18.2	21.2	20.3	0.09

f_b , brick compressive strength; f_i , mortar compressive strength; h/t , prism slenderness ratio; t_j , joint thickness; f_m , prism peak compressive strength; PS, prism specimen.

4.3. Analytical Results by FEM

A Finite Element Model (FEM) was used to analyze the compressive strength of masonry prisms. The analysis examined the effects of brick unit compressive strength, mortar compressive strength, slenderness ratio, and mortar thickness on the overall masonry performance by evaluating the compressive stress–strain behavior. Additionally, as tabulated in Table 12, the modulus of elasticity of the masonry prisms (E_m) was derived by dividing the compressive stress to strain in the elastic region of the stress–strain curve, presented in Figure 16.

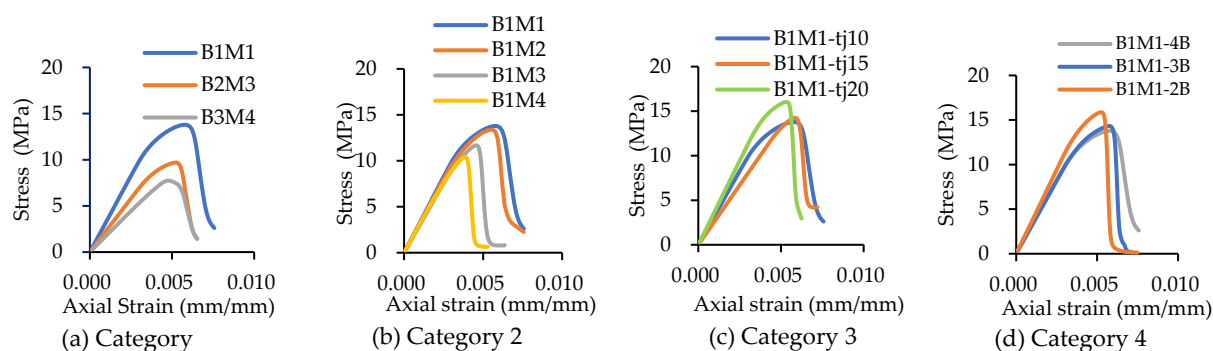
The results for Categories 1 and 2, shown in Figure 16a,b, indicate that the peak compressive strength (f_m) and strain at peak compressive strength (ep_m) is highest in the masonry prisms with the highest brick unit (f_b) and mortar compressive strengths (f_i), i.e., the B1M1 prism in both categories. However, ep_m is not much different between prisms of this category, ranging between 0.0058 and 0.0048. This finding is consistent with previous studies, which have demonstrated that higher-strength materials contribute to enhanced masonry performance due to their ability to resist applied loads better and distribute stress more effectively [17,46–51]

The results for Category 3, shown in Figure 16c, indicate that increasing the mortar joint thickness (t_j) from 10 mm (B1M1- t_j 10) to 20 mm (B1M1- t_j 20) increases masonry prism compressive strength from 13.8 MPa to 16 MPa. In contrast, the strain at peak compressive strength slightly decreases from 0.0058 to 0.0039. It is worth noting that the compressive strength of the mortar joints is greater than that of the brick units (see B1 and M1 results in Tables 8 and 9, respectively).

The results for Category 4, shown in Figure 16d, indicate that decreasing the slenderness ratio (h/t) from 3.3 (B1M1-3.3) to 1.6 (B1M1-1.6) increases both the compressive strength and the strain at peak compressive strength of the masonry prisms. This finding aligns with the literature [49], suggesting that lower slenderness ratios reduce the susceptibility to buckling and enhance the load-bearing capacity of masonry structures.

Table 12. Masonry prisms' mechanical properties from FEM analysis.

Category	Prism	Peak Strength	Strain at Peak Strength	Modulus of Elasticity	E_m/f_m
		f_m (MPa)	ep_m (mm/mm)	E_m (MPa)	
Category 1	B1M1	13.8	0.0058	3125	226
	B2M3	9.7	0.0052	2320	239
	B3M4	7.7	0.0048	1800	234
Category 2	B1M1	13.8	0.0058	3125	226
	B1M2	13.4	0.0056		233
	B1M3	11.7	0.0045		267
	B1M4	10.4	0.0039		300
Category 3	B1M1-tj10	13.8	0.0058	3125	226
	B1M1-tj15	14.2	0.0057	2672	188
	B1M1-tj20	16.0	0.0053	3623	226
Category 4	B1M1-4B	13.8	0.0058	3130	227
	B1M1-3B	15.0	0.0055		209
	B1M1-2B	15.9	0.0053		197
Average of E_m/f_m				230	

**Figure 16.** Stress–strain relationship of masonry prisms obtained from FEM analysis results.

5. Discussion

As shown in Table 9, the average value of the compressive strengths for first, second, and third-class clay bricks were 14.2 MPa, 10.6 MPa, and 8.2 MPa, respectively. This classification is currently not included in the Afghanistan Buildings Code (ABC), specifically in Chapter 7, which addresses the design and analysis of masonry structures.

A comparison of the compressive strength test results with the FEM analysis demonstrated that both displayed similar trends, as shown in Figure 17. The experimental and FEM results for Categories 1 and 2, shown in Figure 17a,b, both indicate that as the mortar compressive strength (f_i) increases, the prism strength (f_m) also increases.

To examine the extent of the increase in f_m , Table 13 shows the Category 2 prisms in three pairwise comparisons (Cases 1, 2, and 3) with f_i as the only variable and f_b , h/t , and t_j as constants. In Case 1, a 45% difference in f_i between B1M1 and B1M2 leads to a 19% difference in f_m . Similarly, in Case 2, comparing B1M2 to B1M3, a 77% difference in f_i resulted in an 11% difference in f_m , and in Case 3, a 34% difference in f_i resulted in a 7% difference in f_m between B1M3 and B1M4. Therefore, the normalized values show that, on average, for every 5% increase in f_i , there is a corresponding 1% increase in f_m .

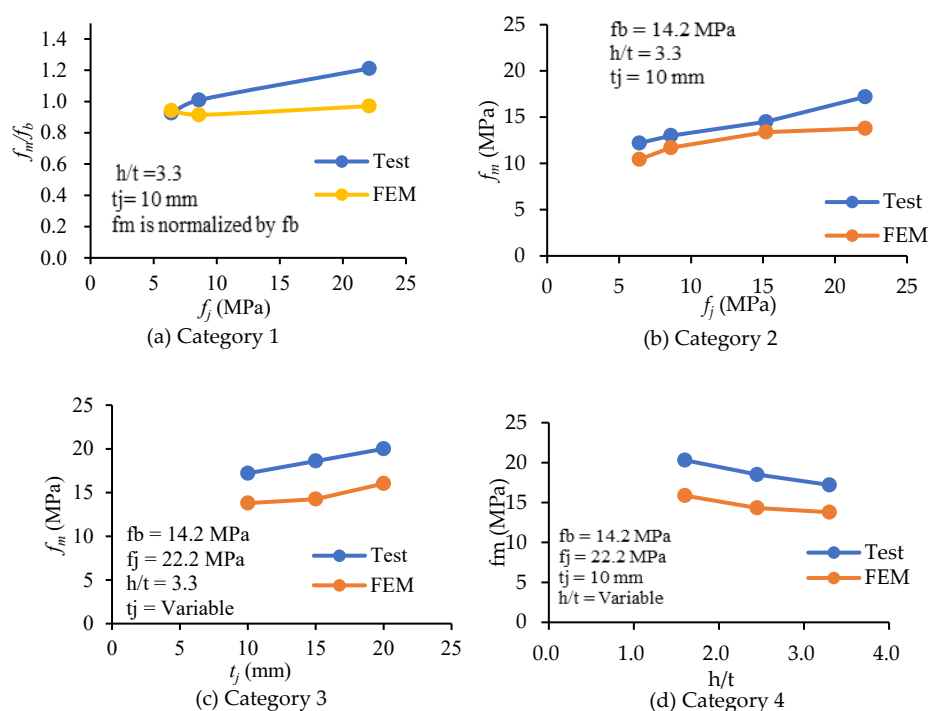


Figure 17. Comparison of test results and FEM modeling masonry prisms' peak compressive strength.

Table 13. Mortar compressive strength (f_j) effect on prism compressive strength.

Prisms description		Compressive Strength (MPa)		Difference Between f_j and f_m of the Pair Prisms of Each Case				
		f_j	f_m	Subtraction *		Ratio (%) **		Normalization ***
				f_j (MPa)	f_m (MPa)	f_j	f_m	
Case 1	B1M1	22.1	17.2	6.9	2.7	45%	19%	2.4
	B1M2	15.2	14.5					
Case2	B1M2	15.2	14.5	6.6	1.4	77%	11%	7.2
	B1M3	8.6	13.1					
Case 3	B1M3	8.6	13.1	2.2	0.8	34%	7%	5.3
	B1M4	6.4	12.3					

* Subtraction: The difference between f_j and f_m for each pair of prisms in each case, such as f_j : $22.2 - 15.2 = 6.9$ MPa and f_m : $17.2 - 14.5 = 2.7$ MPa (Case 1). ** Ratio (%): The rational difference between f_j and f_m for each pair of prisms in each case, such as f_j : $6.9/15.2 \times 100 = 45\%$ and f_m : $2.7/14.5 \times 100 = 19\%$ (Case 1). *** Normalization shows the relative difference of f_j normalized by f_m , such as: $45\%/19\% = 2.4$ (Case 1).

As shown in Table 14, the compressive strength of prism specimens (f_m) increases as the brick unit's (f_b) compressive strength increases. For example, a comparison of B1M3 and B2M3 (Case 1) and B1M4 and B3M4 (Case 2), where f_j , h/t , and t_j are constant, and f_b is the only variable in both cases, represents the direct effect of f_b on f_m . In Case 1, a 34% difference in f_b resulted in a 31% difference in f_m between the prisms, and in Case 2, a 65% difference in f_b resulted in a 62% difference in f_m .

Table 14. Brick unit compressive strength (f_b) effect on prism compressive strength.

Prisms description			Compressive Strength (MPa)		Difference Between f_b and f_m of the Pair Prisms of Each Case				
			f_b	f_m	Subtraction *		Ratio (%) **		Normalization ***
					f_b (MPa)	f_m (MPa)	f_b	f_m	
Case 1	B1M3	Category 2	14.2	13.1	3.6	3.1	34%	31%	1.1
	B2M3	Category 1	10.6	10.0					
Case 2	B1M4	Category 2	14.2	12.3	5.6	4.7	65%	62%	1.1
	B3M4	Category 1	8.6	7.6					

* Subtraction shows the difference between f_b and f_m for each pair of prisms in each case, such as f_b : $14.2 - 10 = 3.6$ MPa and f_m : $13.1 - 10.0 = 3.1$ MPa (Case 1). ** Ratio (%) shows the rational difference between f_b and f_m for each pair of prisms in each case, such as f_b : $3.6/10.6 \times 100 = 34\%$ and f_m : $3.1/8.6 \times 100 = 31\%$ (Case 1). *** Normalization shows the relative difference of f_b normalized by f_m , such as: $34\%/31\% = 1.1$ (Case 1).

For Category 3 prisms, the results from both experimental tests and FEM analysis, shown in Figure 17c, indicate that increasing the mortar joint thickness (t_j) from 10 mm to 20 mm enhances the compressive strength of masonry prisms (f_m), while slightly decreasing the strain at peak compressive strength. This is shown by the increase in f_m from 17.2 MPa to 20 MPa between B1M1- t_j 10 and B1M1- t_j 20 (refer to Table 11) and the shift in the strain at peak compressive strength for B1M1- t_j 20 on the stress–strain graph (refer to Figure 15c). This increase is substantial, considering that if f_b , f_j , and h/t are kept constant, increasing t_j by 5 mm (i.e., from 10 mm to 15 mm or 15 mm to 20 mm) results in an average of 8% increase in the compressive strength of the masonry (determined by the differences in average f_m values between B1M1- t_j 10, B1M1- t_j 15, and B1M1- t_j 20, as shown in Table 15).

Table 15. Joint thickness (t_j) effect on prism compressive strength.

Prisms' description			t_j (mm)	f_m (MPa)	Difference Between t_j and f_m of the Pair Prisms of Each Case		
					t_j (mm)	f_m (MPa)	Average
Case 1	B1M1- t_j 10	Category 3	10.0	17.2	5	1.4	8%
	B1M1- t_j 15		15.0	18.6			
Case2	B1M1- t_j 15	Category 3	10.0	18.6	5	1.4	8%
	B1M1- t_j 20		15.0	20.0			

* Subtraction: The difference between t_j and f_m for each pair of prisms in each case, such as t_j : $15 - 10 = 5$ mm and f_m : $18.6 - 17.2 = 1.4$ MPa (Case 1). ** Ratio (%) shows the rational difference between f_m of each pair of prisms in each case, such as f_m : $1.4/17.2 \times 100 = 8\%$ (Case 1).

This behavior can be attributed to the superior load distribution capabilities of thicker mortar joints, which mitigate stress concentrations and improve the structural integrity of masonry prisms. A recent study by Nazimi et al.[46] occurs in scenarios where the compressive strength of the mortar exceeds that of the brick units. Furthermore, increasing the tensile stress area enhances the tensile strength of the section. Consequently, increasing the thickness of the mortar not only boosts the tensile strength of the mortar but also improves the compressive strength of the masonry. These findings, corroborated by both the experimental tests and FEM results, underscore the critical role of mortar thickness in determining the strength of masonry structures.

Lastly, the comparison of the results of the Category 4 prism specimens, shown in Figure 17d, indicates the influence of the slenderness ratio (h/t) on compressive strength. As h/t decreased from 3.3 in the four-brick prisms to 1.6 in the two-brick prisms, the compressive strength (refer to Tables 11 and 12) and the strain at peak compressive strength (refer to Figure 15d and Table 12) increased. Also, as shown in Table 16, the difference

between Case 1 and Case 2 is specifically highlighted, where a 5.5% increase in the slenderness ratio resulted in a 1% decrease in masonry compressive strength (f_m).

These findings emphasize optimizing slenderness ratios in masonry design to maximize compressive strength and overall structural stability. To reflect a practical condition, a 2.8 m high wall with a thickness of 0.35 m and a slenderness ratio of 8 is one of Afghanistan's typical masonry wall construction scenarios (Case 3). Based on the slenderness effect observed in Cases 1 and 2, this wall would have a compressive strength of 12.7 MPa if B1 brick and M1 mortar with a 10 mm joint thickness were used. Careful consideration of slenderness ratios is crucial for designing efficient and resilient masonry structures capable of performing well under various loading conditions. These findings highlight the importance of optimizing slenderness ratios in masonry design to maximize compressive strength and overall structural stability.

Table 16. Slenderness ratio (h/t) effect on prism compressive strength.

Case No	Prism or Wall Description	h/t	f_m (MPa)	Difference Between h/t and f_m of the Pair Prisms of Each Case						
				Subtraction *		Ratio (%) **		Normalization ***		
				h/t	f_m (MPa)	h/t	f_m	$(h/t)/f_m$	Average	
Case 1	B1M1-4B	3.3	17.2	0.85	−1.3	34%	−7%	−4.9	−5.5	
	B1M1-3B		2.5							18.5
Case2	B1M1-3B	2.5	18.5	0.85	−1.8	53%	−9%	−6.0		
	B1M1-2B		1.6							20.3
Case 3	B1M1-h:2.8-t:0.35	Wall	8.0	12.7	4.7	−4.5	142%	26%		−5.5
	B1M1-4B	Category 4	3.3	17.2						

* Subtraction shows the difference between h/t and f_m for each pair of prisms in each case, such as h/t : $3.3 - 2.5 = 0.85$ and f_m : $(17.2 - 18.5) \text{ MPa} = -1.3 \text{ MPa}$ (Case 1). ** Ratio (%) shows the rational difference between h/t and f_m for each pair of prisms in each case, such as h/t : $0.85/2.5 \times 100 = 34\%$ and f_m : $-1.3/17.2 \times 100 = -7\%$ (Case 1). *** Normalization shows the relative difference of h/t normalized by f_m , such as: $34\%/-7\% = -4.9$ (Case 1), 77% (Case 1).

In general, the FEM gave underestimated values for the masonry prism compressive strength (f_m) across all categories. On average, FEM underestimated f_m by 10% compared to the experimental tests, as indicated in Figure 18. This discrepancy could be due to modeling deficiencies, material properties other than compressive strength, mesh sensitivity, and the average coefficient of variation (CoV) of 9% in the test results for masonry prism specimens reported in Table 11.

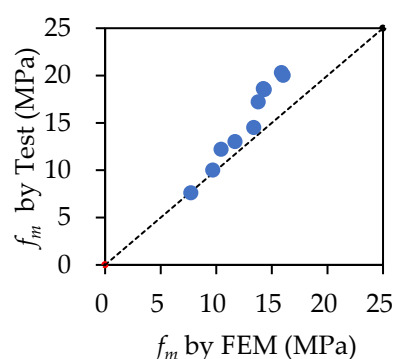


Figure 18. Masonry prism compressive strength test vs. FEM.

The FEM analysis highlights how strain behavior varies with changes in brick-and-mortar strength, mortar joint thickness, and slenderness ratio. Thicker mortar joints reduce strain by improving stress distribution, while lower slenderness ratios enhance ductility by mitigating the risk of buckling under load.

The modulus of elasticity (E_m) results in Table 12 show how the stiffness of the masonry prisms is influenced by the compressive strength of the materials (f_b and f_j). Higher material strengths result in higher E_m values. In contrast, joint thickness and slenderness ratio have minimal impact on E_m . On average, the ratio of E_m to f_m is 230, corresponding to $E_m = 230 \times f_m$. These findings underscore the relationship between material stiffness and compressive behavior, which is essential for optimizing masonry design.

6. Conclusions

This investigation into the compressive strength of clay brick masonry materials in Nangarhar, Afghanistan, using both experimental testing and finite element model (FEM) analysis, provides significant insights into the behavior of masonry prisms under various conditions.

This research determined the average compressive strengths of first, second, and third-class brick units (denoted B1, B2, and B3) to be 14.2 MPa, 10.6 MPa, and 8.2 MPa, respectively. The average compressive strengths for the M1 (1:3), M2 (1:4), M3 (1:6), and M4 (1:6.5) mortars were 22.1 MPa, 15.2 MPa, 8.6 MPa, and 6.4 MPa, respectively.

Based on these values of brick unit (f_b) and mortar (f_j) compressive strengths, specific values for the compressive strength (f_m) of the three types of brick masonry commonly used in Nangarhar are obtained: 17.2 MPa for first-class (B1M1), 10.0 MPa for second-class (B2M3), and 7.6 MPa for third-class (B3M4), with corresponding strain values of 0.0058, 0.0052, and 0.0048, respectively. The effects of the influencing parameters brick compressive strength (f_b), mortar compressive strength (f_j), joint thickness (t_j), and slenderness ratio (h/t), on the prisms' f_m values are summarized as follows:

- A change in f_b results in a corresponding equal change in f_m ,
- A 5% increase in f_j corresponds to a 1% increase in f_m ,
- An increment of t_j from 10 mm to 15 mm and from 15 mm to 20 mm give an 8% increase in f_m , and
- An increment of 5.5% in the h/t corresponds to a 1% decrease in f_m .

FEM analysis, while generally aligning with the experimental results, showed a slight underestimation of compressive strength by approximately 10%. This discrepancy highlights the need for continuous refinement of modeling approaches and further consideration of the influence of additional factors such as strain, modulus of elasticity, and Poisson's ratio on masonry performance.

The FEM analysis demonstrates that strain at maximum strength (ep_m) behavior in masonry prisms is slightly sensitive to variations in brick strength and mortar strength, joint thickness, and slenderness ratios. The study also shows that the modulus of elasticity (E_m) is primarily influenced by the compressive strength of the brick (f_b) and mortar (f_j). Higher material strengths yield greater stiffness, reflected in higher E_m values. However, joint thickness and slenderness ratio have minimal effect on E_m . On average, the relationship between E_m and f_m in this research is defined by $E_m = 230 \times f_m$.

This research provides valuable guidance for optimizing masonry structural design and construction practices of new buildings and evaluating the seismic capacity of existing masonry buildings in Afghanistan. By emphasizing the influence of material properties, joint dimensions, and geometric factors, this study offers practical recommendations for improving the performance of clay brick masonry structures. Integrating experimental and numerical analyses facilitates a comprehensive understanding of masonry behavior, contributing to safer and more reliable masonry structural design in seismic-prone areas like Afghanistan.

7. Recommendations

Based on this study, the authors recommend:

- Revising Chapter 7 of the ABC to incorporate the compressive strength of masonry materials used in the region.
- The f_b values of 14 MPa, 10 MPa, and 8 MPa for Class 1, 2, and 3 (B1, B2, and B3) clay bricks.
- Table 17 included the compressive strength of masonry walls constructed using local materials from Nangarhar, with a 10 mm joint thickness and different slenderness ratios mentioned in the table. This table is recommended based on the explanation in Section 5, summarized in Table 16.

Table 17. Recommendation of compressive strength (f_m) for masonry walls using local materials from Nangarhar

Slenderness Ratio	f_m Values for Each Brick Class (MPa)		
	B1-Class	B2-Class	B3-Class
$h/t \leq 8$	12	7	5
$10 \geq h/t > 8$	10	6	4
$16 \geq h/t > 10$	5	3	2

- $E_m = 230 \times f_m$, the relationship that theoretically estimates the modulus of elasticity (E_m) from compressive strength (f_m) in masonry structures using local materials from Nangarhar.

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