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Mechanical Properties of Components of Nepalese Historical Masonry Buildings

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Abstract*:* *An earthquake of 2015 caused serious damage on historical monuments in Nepal. The monuments are mostly composed of brick masonry and timber. The purpose of this study was to understand the mechanical properties of bricks, mud mortar, and masonry constituting historical buildings of Nepal. Results showed that the average compressive strength and Young's modulus of unit bricks, mud mortar, and masonry prisms were 5.05 N/mm^2, 1.40 N/mm^2, and 1.70 N/mm^2, and 4.30 x 10^3 N/mm^2, 1.17x 10^3 N/mm^2, and 3.10 x 10^2 N/mm^2, respectively. The Poisson's ratio for unit bricks and mud mortar were 0.238 and 0.147, respectively. Similarly, the average value of shear strength and shear deformation angle of masonry wall were 0.054 N/mm^2 and, 4.46x10^{-2} rad., respectively. We concluded that the results of this study will be a good reference for detailed analysis of historical brick masonry buildings of Nepal in static and dynamic loading.*

Keywords: Mechanical properties; Historical brick masonry; Bricks; Mud mortar; Masonry prism

1. INTRODUCTION

In Nepal, there exists a number of typical structures using brick masonry and timber. The brick masonry is composed of burnt or sun-dried solid brick with mud mortar. Masonry with mud mortar is weak in strength and hence vulnerable to earthquakes. When an earthquake hits Nepal, many of brick masonry structures are severely damaged or in some cases reach global collapse.

A strong earthquake hit Nepal on the 25th of April 2015, followed by a number of aftershocks. The earthquakes caused serious damage on monuments. For the purpose of their reconstruction, a research team including authors started a three-year research project in 2016.

In the present paper, recently carried out experiments on masonry and material constituting them, as a part of the project, are discussed. The paper would contribute to better understanding of mechanical properties of bricks, mud mortar, and masonry composed of these materials.

2. MATERIALS AND METHODS

Uniaxial compression tests were carried out on samples of bricks, mud mortar, and brick masonry to find out the properties such as compressive strength, stress-strain behavior, Young's modulus and so forth. Diagonal compression experiment was carried out on masonry walls to determine the shear parameters. All the samples were manufactured and tested at the same laboratory of KHWOPA Engineering College, Nepal.

2.1 Description of the samples

2.1.1 Unit brick compression experiment

Bricks were taken from a historical building in Bhaktapur, Nepal. The building at least can date back to the 19th century although its exact construction date is not known. It was built in a typical method prevailed during the Malla Dynasty. The dimension of brick was about 200-205 mm in length, 115-135 mm in width and 55-60 mm in height. For the experiment, the brick samples were cut manually from the lengthwise direction making a base of 50mm x 50 mm and a height of 100 mm, approximately as shown in Fig.1.

35 brick samples namely UBC 01 ~ UBC 35 were prepared. The dimensions of bricks are shown in Table 1.

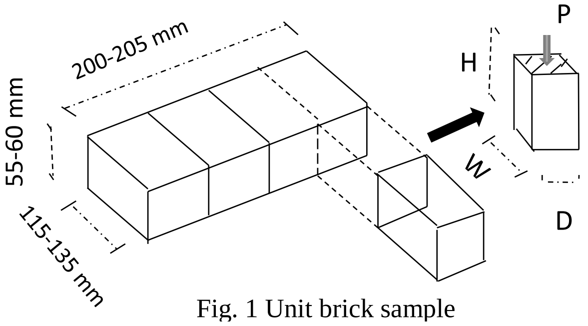

Fig. 1 Unit brick sample

2.1.2 Mud mortar compression experiment

Mud mortar was manufactured in February 2017. The mortar was prepared following the same technique as in the wall making of historical buildings. Five mud mortar cylinders namely MMC 1 ~ MMC 5 were prepared by packing mortar in a plastic mold. The shape and dimensions of mud mortar samples are shown in Fig. 2 and Table 2 respectively.

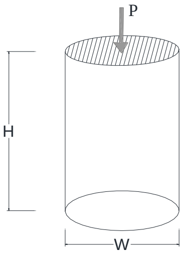

Fig.2. Mud mortar sample

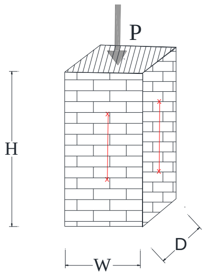

Fig. 3. Prism sample

Table 1. Dimensions of brick samples

Specimen	Width(W), mm	Depth(D), mm	Height(H), mm
UBC 01	48.90	51.77	101.65
UBC 02	51.74	46.60	100.51
UBC 03	50.13	48.57	101.22
UBC 04	50.02	49.56	99.28
UBC 05	49.49	50.12	102.43
UBC 06	51.59	50.45	99.65
UBC 07	52.14	52.10	100.08
UBC 08	49.84	49.23	101.41
UBC 09	50.23	52.00	98.41
UBC 10	50.91	50.18	102.12
UBC 11	46.98	50.13	98.33
UBC 12	51.96	49.91	99.56
UBC 13	49.10	50.25	102.72
UBC 14	48.62	49.47	104.07
UBC 15	46.76	50.99	100.23
UBC 16	48.92	53.03	104.30
UBC 17	50.91	50.76	101.48
UBC 18	50.21	49.46	100.18
UBC 19	50.57	46.94	102.23
UBC 20	51.73	50.13	99.31
UBC 21	48.82	48.48	101.75
UBC 22	51.37	51.50	100.38
UBC 23	50.98	50.50	104.88
UBC 24	50.10	51.00	101.30
UBC 25	50.28	49.65	97.55
UBC 26	51.05	53.90	100.40
UBC 27	50.62	47.72	100.83
UBC 28	50.15	50.22	99.38
UBC 29	50.42	51.62	99.38
UBC 30	48.92	50.87	101.75
UBC 31	51.85	48.02	100.80
UBC 32	48.08	49.78	98.48
UBC 33	50.97	47.88	102.48
UBC 34	47.33	50.22	98.53
UBC 35	48.73	45.88	99.30

Table 2. Dimensions of mud mortar cylinders

Specimen	Diameter (D), mm	Height (H), mm	Area (A), mm^2
MMC 1	49.0	73.0	1887.7
MMC 2	47.8	97.8	1796.4
MMC 3	48.8	98.3	1867.2
MMC 4	47.9	99.7	1805.2
MMC 5	47.4	99.1	1765.2

2.1.3 Masonry prism compression experiment

Three masonry prisms namely C2, C4, and C6 were constructed in February 2017, using the above-mentioned bricks and mud mortar. The width and depth of prism were about 350 mm and 280 mm. Each bricklayer was about 70 mm (including the joint thickness of 10 mm). The shape and dimensions of the prism specimens are presented in Fig. 3 and Table 3, respectively.

Table 3. Dimensions of prism specimens

Specimen	Width (W), mm	Depth (D), mm	Height (H), mm
C2	350.5	284.5	869
C4	349.5	279	871
C6	346.5	279.5	846.5

2.1.4 Diagonal compression experiment

Using the same bricks and mud mortar as in the compression experiments, two wall panels namely D2 and D6 were constructed. The width of wall panel was about 1260 mm and a depth of about 280 mm. Each bricklayer was about 70 mm thick (including 10 mm joint thickness). The shape and dimensions of wall specimens are shown in the Fig. 4 and Table 4, respectively.

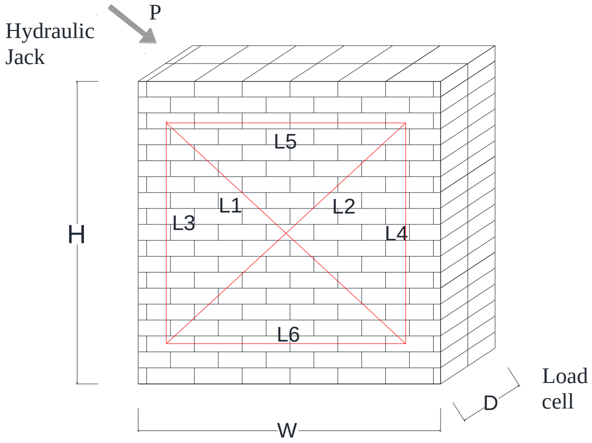

Fig. 4. Masonry wall specimen

Table 4. Dimensions of wall specimens

Specimen	Width (W), mm	Depth (D), mm	Height (H), mm	Area (A), mm^2
D2	1256.5	278.0	1243	3.49×10^5
D6	1268.5	289.5	1262	3.67×10^5

2.2 Description of test procedure

2.2.1 Unit brick compression experiment

The brick samples were tested by 400 kN Universal Testing Machine and load cell made in Japan was used. 5 out of 35 specimens (UBC 01~UBC 05) were measured against strain at the time of loading. Four vertical stain gauges and two horizontal strain gauges were used to measure strain. The compressive stress was determined by the ratio of load per unit area of the samples. Experimental set up is shown in Fig. 5.

Fig. 5. Unit brick compression experiment

Fig. 6. Mud mortar compression experiment

2.2.2 Mud mortar compression experiment

The mortar cylinders were tested in July 2017. The load was applied by Universal Testing Machine of 400 kN capacity. Strain in the horizontal and vertical direction was measured at the back and front center of the cylinder. It is noted that for mortar sample MMC 1, only the load was measured, as the specimen was broken while removing from the plastic mold. Fig. 6 shows the compression test on mud mortar cylinders. Compressive loads were applied on mud mortar specimens and the loads versus deformations were recorded. The compressive stress was determined by the ratio of load per unit area of the samples.

2.2.3 Masonry prism compression experiment

The prism specimens were tested in July 2017. To ensure uniform loading, steel plates of 450 x 400 x 10 mm sizes were set on the top and bottom sides of the prism. The load was applied by means of 500 kN hydraulic jack. The displacement was measured using displacement transducers at the center of four sides of the prism specimen. Fig. 7 shows the compression test conducted on masonry prism. Compressive loads were applied to the prism and the load versus displacement were recorded. The compressive stress was determined by the ratio of load per unit area of the samples.

2.2.4 Diagonal compression experiment

According to a standard test method for the diagonal compression experiment (ASTM 519), the wall panel is required to be rotated by 45 degrees and also the force is applied vertically from the top corner [1].

However, in the present study, the wall panel rests horizontally on one side of the wall, and the force is applied diagonally between the two corners as shown in Fig. 8. In addition, it can also measure the horizontal and vertical displacement of the wall specimen.

For the test set up, the wall panels rest horizontally on a plinth and are positioned so that the load shoe at the bottom corner could be attached to the wall panels. Another load shoe was attached to the diagonally opposite top corner. Two rods on each side of the wall panel connected the two loading shoes with hydraulic jack and load cell at opposite corners.

The diagonal force was applied through the upper corner by a hydraulic jack and a load cell at diagonally opposite bottom corner measured the load. Displacement was measured with six displacement transducers, two each located in diagonal, vertical and horizontal directions, respectively.

Fig. 7. Masonry prism compression

Fig. 8. Diagonal compression experiment

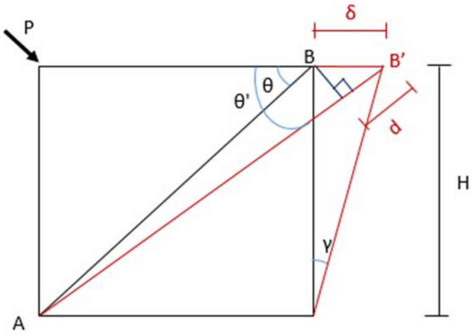

Fig. 9. Calculation method of deformation angle

In this study, the displacement measured by the displacement meter L2 on the specimen is termed as the displacement d on the diagonal tension side. The length of the displacement transducer L4 before the experiment was taken as the test body height H and the shear deformation angle was calculated.

The equation for calculating the shear deformation angle is as follows.

$$\gamma = tan\gamma = \frac{\delta}{L4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, $\delta = \frac{L2' - L2}{\cos\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$

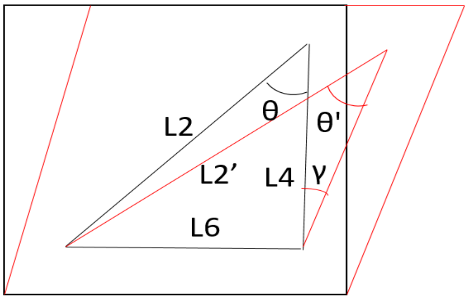

Fig. 10. Calculation method of deformation angle by using cosine theorem

Cosine theorem was used to calculate the deformation angle, using the displacement along tensile deformation as shown in Fig. 10.

$$\gamma = \theta' - \theta \ldots\ldots\ldots\ldots (3)$$

3. RESULTS AND DISCUSSIONS

3.1 Unit brick compression experiment

The compressive strength of each brick specimen is shown in Table 5. The Average compressive strength of unit bricks was 5.05 N/mm^2 and the standard deviation was 2.55 N/mm^2. The histogram chart in Fig. 11 indicates the average compressive strength of samples to be 4 N/mm^2.

The deviation in the compressive strength of samples was large. It can be assumed, that the main reason for it can be the uneven specimen samples due to which eccentric load was exerted on specimens instead of uniaxial load.

Fig. 12 shows the stress-strain diagram of 5 specimen samples (UBC 01~UBC 05).

The Young's modulus and Poisson's ratio of each 5 specimens were calculated by taking the linear regression of data up to one-third of the compressive strength. The values of Young's modulus and Poisson's ratio are shown in Table 6. Despite eccentric loading in samples, Young's modulus has similar values for all the five samples whereas the variations of Poisson's ratio is large. The reason for it can be the existing voids and cracks in the specimens prior to loading showing few negative values.

Table 5. Results of compressive strength of 35 brick samples

Specimen	Compressive strength (N/mm^2)	Specimen	Compressive strength (N/mm^2)
UBC 01	6.17	UBC 19	3.64
UBC 02	3.01	UBC 20	3.93
UBC 03	3.68	UBC 21	7.93
UBC 04	2.66	UBC 22	3.50
UBC 05	4.46	UBC 23	3.47
UBC 06	14.65	UBC 24	5.32
UBC 07	3.20	UBC 25	5.19
UBC 08	2.88	UBC 26	7.61
UBC 09	10.55	UBC 27	8.42
UBC 10	2.90	UBC 28	4.71
UBC 11	4.93	UBC 29	6.61
UBC 12	3.05	UBC 30	4.78
UBC 13	3.92	UBC 31	5.36
UBC 14	2.60	UBC 32	4.80
UBC 15	8.02	UBC 33	4.81
UBC 16	2.96	UBC 34	5.76
UBC 17	3.16	UBC 35	2.54
UBC 18	5.45		
Avg. of UBC 01~UBC 35			5.05 N/mm^2
Std. dev. of UBC 01~UBC 35			2.55 N/mm^2

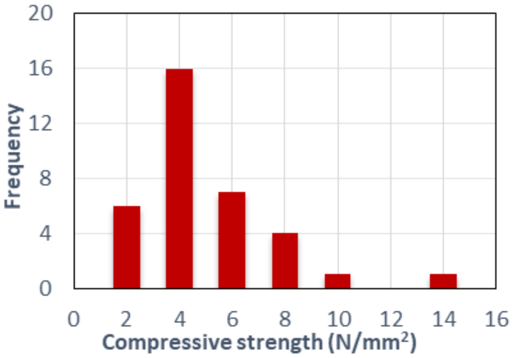

Fig. 11. Histogram of compressive strength of 35 brick samples

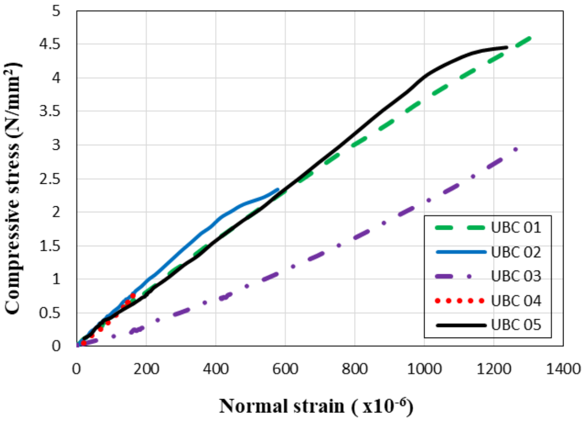

Fig. 12. Stress strain diagram for samples UBC 01~UBC 05

Table 6. Young's modulus and Poisson's ratio of 5 samples (UBC 01~UBC 05)

Specimen	Young's modulus ($x10^3$ N/mm^2)	Poisson's ratio
UBC 01	4.02	0.241
UBC 02	4.86	0.088
UBC 03	1.75*	Negative value *
UBC 04	4.40	Negative value *
UBC 05	3.93	0.384
Average	4.30	0.238

Note: *values are excluded for the calculation of average Young's modulus and Poisson's ratio.

3.2 Mud mortar compression experiment

The results for the compressive strength for the mud mortar compression experiment are shown in Table 7. The average value, the standard deviation, and coefficient of variation was found to be 1.40 N/mm^2, 0.24 N/mm^2, and 16.4% respectively. The specimen MMC 2, MMC 4 and, MMC 5 were only considered for the calculation of average and standard deviation. MMC 1 and MMC 3 were excluded as their compressive strength was higher than 3σ. This may be due to the uneven specimen sample used in the experiment test. It can be assumed that due to the voids and cracks present in samples prior to loading, the variation in results may have occurred. The stress-strain diagram of mortar samples except MMC 1 and MMC 3 are shown in Fig. 13.

The Young's modulus and Poisson's ratio was calculated by taking linear regression of stress-strain data up to one-third of maximum strength. The Young's modulus and Poisson's ratio of mud mortar samples are shown in Table 8. The Young's modulus of sample MMC 4 was excluded for average calculation as the value was inadequate. The average value of Young's modulus and Poisson's ratio for mud mortar was 1.17 x 10^3 N/mm^2.

Table 7. Compressive strength of mud mortar specimens

Specimens	Compressive strength (N/mm^2)
MMC 1	0.58*
MMC 2	1.67
MMC 3	0.65*
MMC 4	1.30
MMC 5	1.22
Avg.	1.40
Std. dev. (σ)	0.24
CV (%)	16.4

Note: *values are excluded for the calculation of average compressive strength

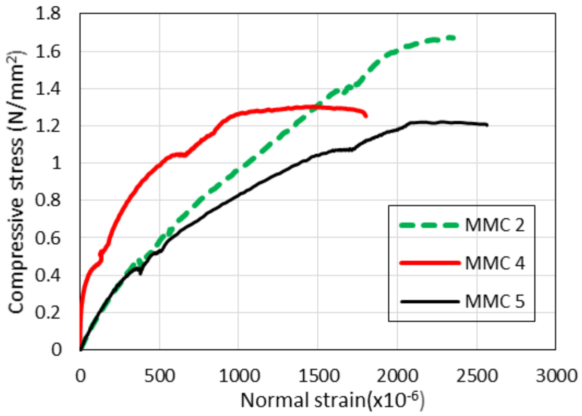

Fig. 13. Compressive stress-strain diagram of mud mortar specimens

Table 8. Young's modulus and Poisson's ratio of mud mortar specimen

Specimens	Young's modulus (x10^3 N/mm^2)	Poisson's ratio
MMC 1	NA	NA
MMC 2	1.20	0.130
MMC 3	0.87	0.193
MMC 4	7.43*	0.167
MMC 5	1.44	0.098
Avg.	1.17	0.147

Note: *values are excluded for the calculation of average compressive strength

3.3 Masonry prism compression experiment

The compressive strength and Young's modulus of prism specimens are shown in Table 9. The average value and the standard deviation for the compressive strength were found to be 1.70 N/mm^2 and 0.08 N/mm^2. The compressive strength values for all the three samples were almost close to each other.

For the prism specimens, a stress-strain relation is shown in Fig. 14. The Young's modulus was calculated by taking linear regression of stress-strain data up to one-third of maximum strength. The average Young's modulus for prism specimen was 3.10 x 10^3 N/mm^2.

In this study, the compressive strength of brick, mud mortar, and brick masonry was examined by a uniaxial compression test. The relationship between brick unit, mortar and masonry compressive strength is given by the following equation as of Euro code 6 (CEN, 2005) [2].

$$f'm = k.\, f'_b{}^{\alpha}\, .f'_j{}^{ß} .... (4)$$

where k, α, and $ß$ are constants and $f'b$, $f'j$ and $f'm$ are compressive strengths of brick, mortar, and masonry, respectively. The values of $k = 0.5$, $\alpha = 0.7$ and $ß = 0.3$, although α and $ß$ has a range of values.

The obtained results are compared with the equation (4). The experiment presented the average compressive strength equal to 5.05 N/mm^2, 1.40 N/mm^2 and 1.70 N/mm^2 for brick, mortar, and masonry, respectively. Applying the value of brick and mortar obtained by the tests, the equation of Eurocode shows 1.72 N/mm^2 for the compressive strength of the masonry which is very close to our result.

Also, masonry compressive strength varies to about 20-50% of the brick's compressive strength. Such a low value is due to the low mortar strength; the higher mortar strength, the higher the prism's strength [3].

In this study, the masonry compressive strength varies to about 30% of the brick's compressive strength.

Table 9. Compressive strength of masonry prism

Masonry prism Specimen	Compressive strength (N/mm^2)	Young's modulus (x10^2 N/mm^2)
C2	1.73	3.41
C4	1.61	2.65
C6	1.77	3.26
Avg.	1.70	3.10
Std. dev.	0.08	0.40
CV (%)	5	0.13

3.4 Diagonal compression experiment

The values of shear stress and shear deformation angle for the specimens D2 and D6 are shown in Table 10. The average shear strength of two specimens was found to be 0.054 N/mm^2. Shear Deformation angle was as explained above. The average value of shear deformation angle calculated was 4.46 x 10^{-2} rad. Fig. 15 shows the shear stress-shear deformation angle of the specimens. It can be understood, that although the shear strength is very low, the deformation capacity exceeds 4% which is fairly high.

From the double shear loading test, conducted on the specimens collected from Kyushu University headquarter building 1 and 3 (Japan), the average shear strength of the specimens (OPS 112 and OPS 121)was found to be 1.12 N/mm^2 [4].

The average shear strength of specimens in our study, was one-twentieth of the average shear strength of specimens from Kyushu University headquarter building. The possible reasons for it could be the use of mud mortar in our study, while the mortar used in Kyushu University headquarter building was cement mortar of compressive strength 29.5 N/mm^2. Another possible reason might be due to the lower value of the compressive strength of brick used in our study (5.05 versus 19.2 N/mm^2).

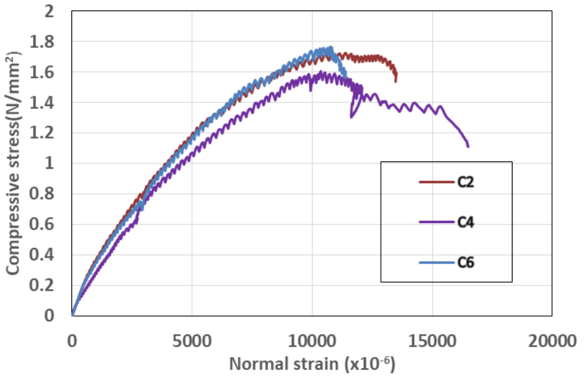

Fig. 14. Compressive stress-strain diagram of masonry prisms

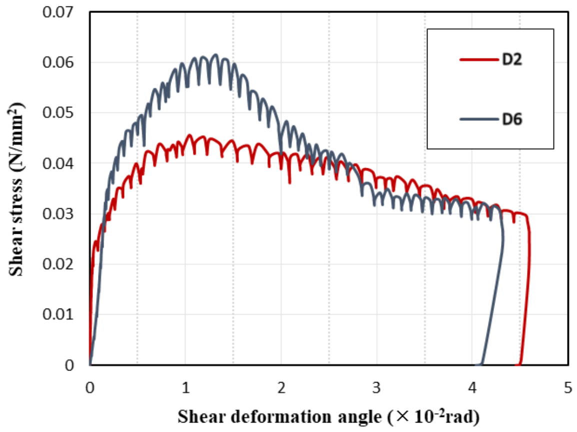

Fig. 15. Shear stress - shear deformation angle

Table 10. Shear strength and deformation angle

Specimen	Shear strength (N/mm^2)	Shear deformation angle (x10^{-2}rad.)
D2	0.046	4.60
D6	0.062	4.32
Average	0.054	4.46

4. CONCLUSIONS

(1) The Average compressive strength of unit brick was 5.05 N/mm^2 with a standard deviation of 2.55 N/mm^2.
The average value of Young's modulus for unit brick was 4.30 x 10^3 N/mm^2 and the Poisson's ratio was 0.238.

(2) The average compressive strength of mud mortar was 1.40 N/mm^2 with a standard deviation of 0.24 N/mm^2.
The average value of Young's modulus and Poisson's ratio was 1.17 x 10^3 N/mm^2 and 0.147, respectively.

(3) The average compressive strength of masonry prism was 1.70 N/mm^2 with a standard deviation of 0.08 N/mm^2. Despite the large standard deviations in results of constituent materials (unit bricks and mud mortar), the standard deviation of compressive strength of masonry prisms was low.
The average value of Young's modulus for masonry prism was 3.10 x 10^3 N/mm^2.

(4) The average shear strength of wall specimens was 0.054 N/mm^2 which is about one-twentieth of the shear strength value of Japanese brick masonry. However, the value of the shear deformation angle was found exceeding 4%, indicating a high deformation capacity.

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