Experimental testing and comparison between historical and traditional masonry brick

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Abstract. The historical masonry brick buildings are important structural symbols due to their old construction time. It is necessary to investigate the mechanical properties of the masonry brick building to evaluate the structural behaviour during service life. Here, the research focused on finding out the compressive strength of brick unit, mortar and brick prism model. Two types of mortar and brick unit are adopted, historical and traditional, and the comparison between the results is implemented. The historical brick and mortar used experimentally in this study were taken from the Imam Ali holy shrine structure (built 300 year before) during its rehabilitation. The traditional brick is Iranian yellow brick which is used in repairing process of two minarets now. The traditional mortar is the Iraqi gypsum which is available in the local market. The tests of mortar cubes and brick units are conducted according to Iraqi Standards and the British Standards is adopted for brick prism models. The experimental testing is carried out in the lab of faculty of engineering at university of kufa. The strain gauges and LVDT instruments are used with the acquisition system device to record and save data. The results of compressive strength and mass density for historical and traditional brick unit and mortar are exhibited. Also, the results of compressive strength, stress-strain curve, load-displacement curve and modulus of elasticity for historical and traditional brick prism models are displayed and discussed. In addition, the compressive strength of brick prism models using empirical equation are estimated. The comparison between the results of historical and traditional brick units, gypsum mortar types and brick prism models are carried out. The historical brick prism model has mechanical properties weaker than the traditional and there is a difference in the compressive strength of the historical brick prism model between the empirical equation and testing results.

Keywords: Mortar, masonry prism, mechanical properties, modulus of elasticity, historical brick.

1. Introduction
Due to the important of the historical buildings were erected from masonry bricks, it is necessary to investigate its structural behavior and mechanical properties to be satisfied under service life. Mechanical properties of masonry brick, compressive strength, modulus of elasticity, are necessary to evaluate the historical building behavior using finite element analysis. The evaluation of the structures includes the static, dynamic analysis and could use that in the structural health monitoring [1]. Many researchers carried out studies to investigate the material properties of brick unites, mortars and brick prism. Sahlin (1971) suggested that within practical limits, the wall strength is dependent on mortar
strength as well as brick unit strength [2]. It was concluded that the brick wall strength is about 25% to 50% of individual brick unit strength. The specifications FEMA273-Siesmic Rehabilitation Guidelines-USA (1997) classified the masonry compressive strength depending on conditions and taken as at the most 900 psi for masonry in good condition, 600 psi for masonry in fair condition and 300 psi for masonry in poor condition [3]. Also, it could estimate the Young’s modulus of elasticity of masonry panel as \( E_m = 550 f_m \). Tomazevic (1999) reported in his publisher Earthquake-resistant design of masonry buildings that the compressive strength of masonry brick could be estimated from his proposed equation as follows \([1]\) \( f_b = K f_b^{0.65} f_m^{0.25} \) depending on the compression test of brick unit and mortar cube [4]. Where \( f_b \) a compressive strength of brick unit in MPa, \( f_m \) is a compressive strength of mortar in MPa and \( K \) is a constant parameter and its value depends on the classification of masonry prism type. Naseer (2009) implemented a performance behavior of confined brick masonry buildings under seismic demand [5]. The researcher suggested relation to extract the value of modulus of elasticity that is 342 times the compressive strength of masonry (\( E_m = 342 f_m \)). Foytong et al. (2016) investigated on brick types and masonry prisms under compressive loading [6]. They suggested that the average compressive stress of masonry prisms, made from all forms of clay brick, is 10.8 MPa and it is higher than the average compressive stress of those made from hollow block and lightweight block (2.62 MPa). Phaiju & Pradhan (2018) executed experimental work to investigate the mechanical properties of brick unit and masonry panel [7]. They concluded that the full-scale selected brick units \((230 \times 110 \times 50)\) mm and the scaled down brick units \((77 \times 34 \times 17)\) mm have the average compression strength of 11.12 MPa and 13.73 MPa, respectively, while the compression strength of masonry panel is 2.5 MPa. Also, it was concluded that the mortar samples have average compressive strength of 3.8 MPa. Their results were displayed that the masonry panel has about 23% strength of brick unit and the Young’s modulus of masonry panel estimated from the experiment is about 2700 MPa. They suggested that the Young’s modulus of masonry panel could be estimated by relation as \( E_m = 1085 * f_m \). This research is focused on carrying out experimental testing to investigate the mechanical properties, compressive strength and modulus of elasticity, for two types of brick prism classified as a historical and traditional brick. Also, the comparative study is implemented between the results of the adopted brick unit, mortar and brick prism types. These results could be used in future research to assist the structural behavior of the historical building of Imam Ali holy shrine.

2. **Experimental testing**

The experimental tests were carried out in the Lab of Faculty of Engineering at University of Kufa. The material tests include the mortar of gypsum and two types of brick units, historical and traditional. Also, the masonry brick prisms were built from gypsum mortar and the two types of brick. The historical brick was gathered from Imam Ali holy shrine structure during its rehabilitation. The traditional brick is Iranian yellow brick that used in the repairing process in minaret of Imam Ali structure and it was bought from the market.

2.1. **Mortar testing**

For mortar material, the compressive strength was tested using compression test machine in the Lab according to the Iraqi Standards (28-2010) [8]. The mortar used in this study consists of two types of gypsum, historical and traditional. The casted historical mortar cutting as cubic from remaining rubble of demolition was produced from repairing in several locations in the Imam Ali Holy Shrine structure with dimensions of \((50 \times 50 \times 50)\) mm. The second type of mortar is traditional gypsum from market, preparing and the curing of samples were in six days in lab as cubic with dimensions of \((50 \times 50 \times 50)\) mm. According to Iraqi Standards (27-1988) [9], the traditional mortar was undergoing to standard tasting consistence test to determine the (water/gypsum) ratio, and setting time test. The compressive strength test of gypsum cubic samples was conducted in 7-day age using loading rate of 1 kN/sec according to Iraqi Standards (28-2010) [8] as shown in figure 1.
2.2. Brick compression testing

For brick samples, the compressive strength was tested using compression test machine in the Lab according to the Iraqi Standards (25-1988) [10]. The dimensions of the historical brick used in the testing, was taken from remaining rubble of demolition was produced from repairing of the structure of Imam Ali holy shrine, are 160 mm×160 mm×40 mm. While, the dimensions for traditional brick samples, was brought from the local market, are 198 mm×198 mm×25 mm. The number of samples for each type of brick is three bricks. The compressive strength test was carried out with loading rate of 140 kg/cm²/min according to Iraqi Standards (25-1988) [10], as shown in figure 2.
2.3. Brick masonry prism compression testing

For each type of brick (historical and traditional), three prism samples were built in the lab according to British standards (EN 1052-BS1999) [11] by former staff with the researchers. The dimensions of historical brick prism are 580 mm × 345 mm × 160 mm, while for traditional brick prisms are 590 mm × 420 mm × 198 mm. The mortar used in erecting the prisms for both types of brick is gypsum material. The mortar consists of traditional gypsum and water in mixing weight identified according to Iraqi Standards (27-1988) [9]. The prism model contains 20-brick as 2-brick for each 10-row and 26-brick as 2-brick for each 13-row for historical and traditional brick, respectively. The strain gauges used in the model testing were fixed in 4-position using special type of epoxy. The main strain gauge is installed in the middle of the prism model, whereas the others are installed in different locations and used for checking, as shown in figure 3. The Linear Variable Differential Transformer (LVDT) was used to measure the displacement during applying load. LVDT was installed in the middle third of prism model fixed by its weighting base. Also, a small plate was fixed inside the model during erecting process in the upper of the LVDT to measure the displacement by its gauge spring, as shown in figure 3.

![Figure 3. Erection of brick prism model in lab with all installed instruments.](image)

The compressive strength test of masonry prism models was conducted in lab using standard Universal Testing Machine (UTM) according to British standards (EN 1052-BS1999) [11]. The test is carried out on the prism samples at the seventh day after the curing process finished in 6-day depending on the results of the mortar testing standards. In order to apply the loads uniformly, the rigid mild steel beam was set in the upper side of the prism model as well as a 10 mm steelplate putted in the base during erecting the prism, as shown in figure 4. The prism model was translated the UTM by using Crane machine with 500 kg. The loading test of prism model is implemented with loading rate of 0.03 kN/sec. The data recorded from strain gauges and LVDT was transformed and saved to acquisition device linked
with PC in the lab with all tools, cables and equipment. The data was used to estimate the strain versus stress relation and plotted the relation curve to identify the Young’s modulus.

3. Results and comparison

3.1. Mortar material
The results of standard tasting consistence test for gypsum mortar show that the rate of water is 0.8 cm³/g and the setting time is 9 min. The compressive strength test for traditional gypsum mortar cubes was conducted in 7-day age as well as for casted historical mortar. The test results of gypsum mortar cube, for the historical mortar samples, gave average compressive strength of 7.85 MPa, while for traditional mortar samples were average compressive strength of 6.77 MPa. The difference ratio percent between the historical and traditional mortar in compressive strength was 13.76%, as listed in table 1. According to the results and the British standards (EN 1052-BS 1999), it is allowable to conduct the tests of prism
brick. Depending on the dimensions of cube, the loading area for historical and traditional mortar cube is 2500 mm$^2$.

### Table 1. Compressive strength values of mortar cube.

| Mortar Cubes ID | Historical mortar | Traditional mortar | Percent Difference Ratio (%) |
|-----------------|-------------------|--------------------|------------------------------|
|                 | Max. Load (kN)    | Average of Compressive Strength (MPa) | Max. Load (kN) | Average of Compressive Strength (MPa) |                  |
| 1               | 19.5              | 7.80               | 20                         | 8.00                         |                  |
| 2               | 20.4              | 8.16               | 14.8                       | 5.92                         | 6.77             | 13.73            |
| 3               | 19.0              | 7.60               | 16                         | 6.40                         |                  |

### 3.2. Brick sample

#### 3.2.1. Compressive strength of brick units

The test of brick, for historical brick units, gave average compressive strength of 6.5 MPa, however for traditional brick units had compressive strength of 6.15 MPa. That means the historical brick units have a compressive strength greater than traditional brick units in percent of 5.38% as listed in Table 2. As mentioned previously about the dimension of selected both types of brick unit, the loading area for historical is 25600 mm$^2$ and for traditional is 39204 mm$^2$.

### Table 2. Compressive strength results of brick units.

| Brick Units ID | Max. Load (kN) | Average of Compressive Strength (MPa) | Max. Load (kN) | Average of Compressive Strength (MPa) | Percent Difference Ratio (%) |
|----------------|----------------|--------------------------------------|----------------|--------------------------------------|------------------------------|
| 1              | 182.0          | 7.11                                 | 201.3          | 5.13                                 |                              |
| 2              | 206.7          | 8.07                                 | 265.9          | 6.78                                 | 6.15                         | 5.38                        |
| 3              | 110.2          | 4.30                                 | 256.4          | 6.54                                 |                              |

#### 3.2.2. Mass density of brick units

The mass density of brick unit was estimated after measuring the weight and dimensions of each brick. For historical and traditional brick units, the average mass density was 1524.08 kg/m$^3$ and 1675.34 kg/m$^3$, respectively, as listed in Table 3. The percent difference ratio between the historical and traditional brick units was -9.92%.

### Table 3. Mass density values of brick units.

| Brick Units ID | Weight (kg) | Volume (m$^3$) | Average Mass Density (kg/m$^3$) | Weight (kg) | Volume (m$^3$) | Average Mass Density (kg/m$^3$) | Percent Difference Ratio (%) |
|----------------|-------------|----------------|---------------------------------|-------------|----------------|---------------------------------|------------------------------|
| 1              | 1.5807      | 1024x10$^{-6}$ | 1543.65                         | 1.6403      | 980x10$^{-6}$  | 1673.60                         |                              |
| 2              | 1.4461      | 1013x10$^{-6}$ | 1427.55                         | 1.6443      | 980x10$^{-6}$  | 1677.69                         | -9.92                        |
| 3              | 1.6493      | 1030x10$^{-6}$ | 1601.04                         | 1.6414      | 980x10$^{-6}$  | 1674.73                         |                              |
3.3. Brick prism model

3.3.1. Compressive strength of brick prism model

After conducting the compressive strength of brick prism with all its process as mentioned previously, the results show that the historical brick prism had average compressive strength of 1.21\textsuperscript{71} MPa. However, the compressive strength for traditional brick prism was 2.05\textsuperscript{3} MPa, as listed in table 4. The historical brick prism has a compressive strength value less than traditional brick prism with percent difference ratio of -68.69%. The loading area of erected brick prism for historical type is 55200 mm\textsuperscript{2} and for traditional type is 83160 mm\textsuperscript{2}.

| Table 4. Summary of compressive strength value of brick prisms. |
|---------------------------------------------------------------|
| Brick | Historical brick prism | Traditional brick prism |
| prism ID | Max. Load (kN) | Compressive Strength (MPa) | Average of Compressive Strength (MPa) | Max. Load (kN) | Compressive Strength (MPa) | Average of Compressive Strength (MPa) | Difference (MPa) |
| 1 | 62.50 | 1.132 | 188.02 | 2.261 |
| 2 | 63.10 | 1.143 | 1.217 | 184.00 | 2.213 | 2.053 | -0.836 |
| 3 | 76.01 | 1.377 | 140.01 | 1.684 |

Also, the compressive strength of brick prism can be approximately estimated by equation related to the compressive strength of both brick unit and mortar cube as mentioned previously. According to Tomazevic equation [4], the compressive strength for each prism was calculated and listed in table 5. The constant parameter used in the equation for this type of clay brick prism is 0.5 [5].

| Table 5. Summary of compressive strength for brick prisms according to Miha’s equation |
|---------------------------------------------------------------|
| Brick Prism ID | Compressive Strength of Brick Unit $f_b$, (MPa) | Compressive Strength of Mortar Cube $f_m$, (MPa) | Compressive Strength of Brick Prism $f_k$, (MPa) | Average of Compressive Strength (MPa) | Difference (MPa) |
| Historical | | | |
| Brick Prism | H-P-1 | 7.11 | 7.80 | 2.99 |
| | H-P-2 | 8.07 | 8.16 | 3.28 | 2.805 |
| | H-P-3 | 4.30 | 7.60 | 2.14 |
| Traditional | | | |
| Brick Prism | T-P-1 | 5.13 | 8.00 | 2.43 |
| | T-P-2 | 6.78 | 5.92 | 2.71 | 2.612 |
| | T-P-3 | 6.54 | 6.40 | 2.70 | 0.193 |

It is quite obvious from tables 4 and 5 that the average compressive strength of historical brick prism estimated from equation is bigger than the result value obtained from the test. Whereas the traditional brick prism has average compressive strength value obtained from equation is close to the average value from the test. The results of stress-strain relationship for both types of brick prism, historical and traditional, are shown in figures 5-10. In addition, the load-displacement curves for both types of brick prism models are exhibited in figures 11-16.
Figure 5. Stress-Strain relationship for historical prism-1 (H-P-1).

Figure 6. Stress-Strain relationship for traditional prism-1 (T-P-1).

Figure 7. Stress-Strain relationship for historical prism-2 (H-P-2).

Figure 8. Stress-Strain relationship for traditional prism-2 (T-P-2).

Figure 9. Stress-Strain relationship for historical prism-3 (H-P-3).

Figure 10. Stress-Strain relationship for traditional prism-3 (T-P-3).
Figure 11. Load-Displacement relationship for historical prism-1 (H-P-1).

\[ y = -4.4202x^2 + 30.235x + 15.725 \]
\[ R^2 = 0.8864 \]

Figure 12. Load-Displacement relationship for traditional prism-1 (T-P-1).

\[ y = 0.1439x^2 + 14.915x + 5.1365 \]
\[ R^2 = 0.9962 \]

Figure 13. Load-Displacement Relationship for historical prism-2 (H-P-2).

\[ y = -0.4594x^2 + 10.185x + 3.8002 \]
\[ R^2 = 0.989 \]

Figure 14. Load-Displacement Relationship for traditional prism-2 (T-P-2).

\[ y = 0.1877x^2 + 6.8969x + 7.5628 \]
\[ R^2 = 0.9903 \]

Figure 15. Load-Displacement relationship for historical prism-3 (H-P-3).

\[ y = -2.7593x^2 + 27.601x + 3.4704 \]
\[ R^2 = 0.9994 \]

Figure 16. Load-Displacement relationship for traditional prism-3 (T-P-3).

\[ y = -0.5882x^2 + 19.431x - 2.663 \]
\[ R^2 = 0.9867 \]
It is clear from figures 11-16 that the maximum displacement behavior of traditional brick prism larger in value than the maximum displacement of historical. Also, the maximum displacement recorded was 17.95 mm in traditional brick prism model no.2 (T-P-2), as shown in figure 14.

3.3.2. Modulus of Elasticity of brick prism model
According to British Standards (EN 1052-1-BS1999), the modulus of elasticity $E_i$ is estimated depending on stress-strain curve produced from compressive strength test of brick prism model, as shown in figures 5-10. The modulus of elasticity $E_i$ was calculated as secant modulus from the strain value corresponding to one third of the maximum stress achieved, as given in equation 1:

$$E_i = \frac{F_{i,\text{max}}}{3 \times \varepsilon_i \times A_i}$$  \hspace{1cm} (1)

The results of Modulus of Elasticity for each prism model, depending on the stress-strain relationship and equation 1, were listed in table 6.

| Brick Prism ID | Maximum Stress (MPa) | Modulus of Elasticity (MPa) | Average Modulus of Elasticity (MPa) | Percent Difference Ratio (%) |
|---------------|----------------------|-----------------------------|-----------------------------------|-----------------------------|
| Historical Brick Prism | | | | |
| H-P-1 | 1.132 | 4680.96 | 3387.01 | |
| H-P-2 | 1.143 | 3023.55 | | |
| H-P-3 | 1.377 | 2456.51 | | |
| Traditional Brick Prism | | | | |
| T-P-1 | 2.2609 | 6096.30 | | -60.99 |
| T-P-2 | 2.2126 | 3586.72 | 5452.69 | |
| T-P-3 | 1.6836 | 6675.04 | | |

From table 6, the historical brick prism has modulus of elasticity of 3387.01 MPa, while the traditional brick prism has modulus of elasticity of 5452.69 MPa. The percent difference ratio between the historical and traditional brick prism is -60.99%.

4. Conclusions
This research investigates the compressive strength of gypsum mortar and brick unit for historical type (Imam Ali holy shrine masonry structure) and traditional type (Iranian yellow brick used in repairing) according to Iraqi Standards (27-1988) and (28-2010) and conducts the comparison between them. Also, the investigation of mechanical properties (compressive strength, modulus of elasticity) was carried out for two types of masonry prism (historical and traditional) according to British Standards (EN 1052-BS1999). The research findings can be summarized as follows:

- The average compressive strength of historical and traditional mortar cubesis 7.85 MPa and 6.77 MPa, respectively, while the average compressive strength of historical and traditional brick units is 6.5MPa and 6.15 MPa.
- The average compressive strength of historical mortar cubes and brick units are greater than the average compressive strength of traditional mortar cubes and brick units in 13.76% and 5.38% respectively. These differences can be attributed to the difference in age of historical and traditional cubes. Also, it can be to the difference in thickness between historical and traditional
brick units, whereas the thickness of historical brick units is more than the thickness of traditional brick units.

- The average mass density of historical and traditional brick unit is 1524.08 kg/m³ and 1675.34 kg/m³, respectively. The percent difference ratio between the historical and traditional brick units is -9.92%.

- The average compressive strength of historical and traditional masonry prism obtained from tests is 1.217 MPa and 2.053 MPa, respectively. Whereas, the average compressive strength of historical and traditional masonry prism estimated from the equation is 2.805 MPa and 2.612 MPa, respectively. The difference between the average compressive strength of historical and traditional masonry prism obtained from test and the equation are -0.836 MPa and 0.193, respectively.

- The average modulus of elasticity for historical and traditional masonry prism is 3387.01 MPa and 5452.69 MPa, respectively. The difference in average modulus of elasticity for historical and traditional masonry prism is 2065.68 MPa. These differences can be attributed to the difference in age of brick for both types whereas the historical brick has 300 year before.

- The obtained mechanical properties of historical brick prism can be used in the finite element simulation in future work to study the structural behaviour of historical Imam Ali holy shrine structure.

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