sciendo

Civil and Environmental Engineering
Vol. 17, Issue 2, 401-408, DOI: 10.2478/cee-2021-0043

ESTIMATION OF MECHANICAL PROPERTIES AND MASS DENSITY OF AL-MALWIYA MASONRY

Muhammed Abbas HUSAIN[1,*]

[1] Department of Civil Engineering, College of Engineering, University of Samarra, Iraq.
[*] corresponding author: mhmdabbas@uosamarra.edu.iq

Abstract

This paper presents the first estimation for the mechanical properties and the mass density of the masonry of Al-Malwiya heritage minaret. Many approaches are investigated in order to estimate the modulus of elasticity, shear modulus, Poisson's ratio, and the mass density for this historic masonry. The mechanical properties are estimated by using empirical formulas and analytical equations, while the mass density is estimated after carrying out experimental tests for the extracted samples of the historic mortar. The estimated properties showed relatively low values compared with the newly constructed masonries, but they were interpreted as reasonable for such a historic construction.

Keywords:

Masonry properties;
Masonry estimation;
Heritage masonry;
Empirical formulas;
Al-Malwiya.

1 Introduction

Al-Malwiya is a historic minaret constructed in the city of Samarra, Iraq, during the reign of Al-Mutawakkil Ala-Allah, Abbasid Caliph, in 851 CE. It has a spiral shape, as shown in Fig. 1, and characterized by many values. The structural system of Al-Malwiya is masonry, constructed by units of historic clay bricks of dimensions 27 cm × 27 cm × 7 cm bonded by a mortar of historic gypsum [1].



Fig. 1: Al-Malwiya minaret.

Generally, the structural investigations for the historic masonry buildings are a difficult process due to the lack of documented information and the unavailability of extracting the samples, as well as the complexity due to non-homogeneity and inelastic behavior of such composite structures.

There are many mechanical and physical properties that need to be found prior to investigating the structural behavior of the historic masonry buildings. The modulus of elasticity (Young's modulus), the modulus of rigidity (shear modulus), and Poisson's ratio are considered as the most important mechanical properties in structural analysis. Also, mass density is an essential physical property in computing the self-weight of the masonry which is a basic parameter in performing the structural analysis.

The masonry modulus of elasticity E_m can be obtained by plotting the compression stress-strain curve, then calculating it as a chord modulus of the linear portion, which is defined to be in a range of 5 % to 33 % from the ultimate masonry compressive strength [2]. For an existing masonry, especially in case of heritage buildings, it is difficult to extract the prisms and carrying out experimental tests due to the considerations of preservation of the heritage values, and to avoid causing damage in the masonry structure. Therefore, many approaches have been used by researchers to estimate the value of the modulus of elasticity for an existing and/or heritage masonry buildings. Based on the linear relation between the masonry modulus of elasticity E_m and the masonry compressive strength f_m, many standard codes and researchers presented empirical models to estimate the masonry modulus of elasticity [3-10]. Table 1 shows the most common empirical formulas that have been used in the literature to estimate the masonry modulus of elasticity.

Table 1: Common empirical formulas for the masonry modulus of elasticity.

No.	Author	Empirical formula
1	Paulay and Priestly [3]	$E_m = 750\ f_m$
2	Drydale et al.[4]	$E_m = (210 \text{ to } 1670)\ f_m$
3	CSA [5]	$E_m = 850\ f_m \leq 20000\ MPa$
4	Eurocode 6 [6]	$E_m = 1000\ f_m$
5	Kaushik et al. [7]	$E_m = (250 \text{ to } 1100)\ f_m$
6	MSJC [8]	$E_m = 700\ f_m$
7	Lumantarna et al. [9]	$E_m = 294\ f_m$
8	Costigan et al. [10]	$E_m = (85 \text{ to } 230)\ f_m$

On the other hand, in-situ tests were also used by researchers to evaluate the masonry modulus of elasticity. Guadagnuolo et al. [11] used the double jack test, as a minor destructive test, and Binda and Saisi [12] carried out non-destructive tests to obtain this mechanical property.

Unlike the modulus of elasticity, there is no analytical harmonic method to estimate the masonry shear modulus G_m, but it can be computed by conducting experimental tests for masonry prisms, or by using a ratio from the value of modulus of elasticity as presented in many codes [13]. This ratio is presented by Eurocode 6 [6] and MSJC [8] which states that the value of the shear modulus of the masonry could be taken as 0.4 of the value of masonry modulus of elasticity.

For the Poisson effect, the value of Poisson's ratio v can be also achieved by experimental tests on masonry prism [14], but in absence of the experimental and in-situ tests, the fundamental formula in mechanics, $G = E/2\ (1 + v)$, which relates the Poisson's ratio v with the modulus of elasticity E and the shear modulus G, may be used based on its assumptions [13, 15].

For estimating the mass density of an existing masonry, if the mass densities of the constituent materials (bricks and mortars) are known, then the mass per unit volume of the masonry can easily be computed based on the volumetric ratios of these materials, provided that the construction materials are assumed to be homogenous in a unit volume of the masonry. Also, the non-destructive tests can be used to estimate the mass density of masonry [12].

Over its long age (about 1200 years), Al-Malwiya minaret has been exposed to various effects and weathering factors that necessarily weaken it, structurally, through changing the characteristics of its construction materials and the bonding strength between them. It is therefore necessary to study the structural condition of this ancient minaret in order to assist in the safety and preservation of its values. There is a lack in structural studies of this archeological minaret despite its high values. The only available structural study in the literature is that presented by Husain et al. [1] which reported the predicted value of the masonry compressive strength.

The purpose of this study is to present the first estimation of the properties; modulus of elasticity, shear modulus, Poisson's ratio, and the mass density, which are needed in structural analysis process for the masonry of Al-Malwiya. The results of this study will provide the analyzers

with the necessary characteristics to perform the structural analysis, as well as assisting the investigators by purveying them useful information for further studies regarding this heritage minaret.

2 Methodology

The methodology of this study is developed based on the following limitations:

- Due to high heritage values and to avoid causing structural damage in the construction of the minaret, the process of cutting out masonry prisms, or even applying in situ minor-destructive tests, cannot be performed.

- Due to the complex geometry and ancient texture system of the minaret construction, it becomes difficult to get accurate results by applying the non-destructive tests.

Therefore, the analytical methods are adopted in the current study to investigate the mechanical properties of the masonry. Regarding the estimation of the masonry mass density, experimental tests are conducted to evaluate the mass density for extracted mortar samples, provided that the mass density of the brick units is available in literature, then a developed geometric approach is used to evaluate the masonry mass density.

2.1 Estimating the modulus of elasticity

The most common empirical formulas for computing the masonry modulus of elasticity E_m, which presented in Table 1, are investigated in order to choose the most applicable model for the masonry in current study. It has been noticed that most of the models are developed for cement-mortar based masonries, whereas Kaushik et al. [7] and Lumantarna et al. [9] developed their models based on masonries constructed with mixed mortars composed of cement, lime and sand. Additionally, Costigan et al. [10] focused on studying masonries with various grades of lime mortars. For the masonry of Al-Malwiya, since the mortar is a historic gypsum, which has a comparable strength behavior with the lime mortar, then the models adopted by Kaushik et al. [7], Lumantarna et al. [9], and Costigan et al. [10] are firstly selected, among the models in literature, to be the most applicable models in current study.

2.2 Estimating the shear modulus and Poisson's ratio

The modulus of elasticity E, shear modulus G, and Poisson's ratio v are related in the following fundamental formula, which has been used by many researchers [13, 15]:

$$G = E / 2 (1 + v) . \quad (1)$$

The masonry shear modulus G_m in current study is estimated as a ratio of masonry modulus of elasticity E_m according to the following formula which presented in Eurocode 6 [6] and MSJC [8]:

$$G_m = 0.4 E_m . \quad (2)$$

In fact, Eq. (2) was obtained by substituting the value of $v = 0.25$ into Eq. (1) [13, 15]. Therefore, using Eq. (2) in estimating the shear modulus leads already to the value of 0.25 for the masonry Poisson's ratio provided that Eq. (1) is used to estimate the Poisson's ratio.

2.3 Estimating the mass density

Since the construction system of Al-Malwiya is masonry as shown in Fig. 2, and based on homogeneity assumption, the mass density of the masonry is determined from the values of the mass densities for the construction elements (brick and mortar) and their volumetric ratios.



Fig. 2: The construction system of Al-Malwiya.

The mass density and the dimensions of the historic brick of Al-Malwiya were computed by Husain et al. [1]. For the historic gypsum mortar, six extracted samples are taken from the site of Al-Malwiya to conduct the computations of the mass density of the mortar. Since the mortar samples are irregular as shown in Fig. 3, the volumes of the samples are calculated by using a graduated glass cylinder according to the Archimedes principle (the volume of the immersed solid = the volume of the displaced water). After obtaining the volumes and the mass density for both the bricks and mortar, the total mass density is computed by summing the contributions of the values of unit mass for the brick and mortar, based on their volumetric ratios.



Fig. 3: Samples of the historic gypsum mortar of Al-Malwiya.

3 Results and discussion

3.1 The masonry modulus of elasticity

As aforementioned in the previous section, the empirical models presented by Kaushik et al. [7], Lumantarna et al. [9], and Costigan et al. [10] are basically selected among the other models in Table 1. The model presented by Kaushik et al. [7] was developed after conducting experimental tests for prisms constructed with three levels of mortar strength, namely: weak, intermediate, and strong. These mortars were composed from different mixes of cement-lime-sand. The values of masonry modulus of elasticity were ranging from 250 to 1100 times the compressive strength of the masonry. Lumantarna et al. [9] evaluated the masonry modulus of elasticity for a total of 120 prisms that were either constructed in the laboratory or extracted from old buildings with different mixes of cement-lime-sand mortars. The concluded empirical model presented was E_m = 294 f_m. Costigan et al. [10] presented three empirical formulas in order to estimate the masonry modulus of elasticity based on the regression analysis for the results from experimental tests conducted for masonry prisms, composed of low-strength clay bricks and various grades of lime mortars as shown in Table 2.

Table 2: Empirical models proposed by Costigan et al. [10].

No.	Mortar type	Masonry compressive strength after 1 year [MPa]	Empirical model
1	PC lime M6	> 9.7	$E_m = 230\ f_m$
2	Hydraulic lime NHL5	8.5	$E_m = 130\ f_m$
3	Hydraulic lime NHL3.5	8.9	$E_m = 130\ f_m$
4	Feebly hydraulic lime NHL2	4.8	$E_m = 85\ f_m$
5	Hydrated lime CL90s	4.3	$E_m = 85\ f_m$
- The mix (cement:lime:sand) for M6 is 1:1/2:4, and for other mortars are 0:1:3, - The compressive strength of the clay brick for all cases is 15 MPa.			

Careful investigations are carried out in this study to select the most representative empirical model among the models proposed by Kaushik et al. [7], Lumantarna et al. [9], and Costigan et al. [10]. It is found that the model presented by Costigan et al. [10] for the masonry constructed with hydrated lime CL90s (the model $E_m = 85\ f_m$ in Table 2) is the most appropriate model to be adopted in current study due to three points:

- This model has a masonry compressive strength of 4.3 MPa which is close to the masonry compressive strength of Al-Malwiya that was predicted as 4.1 MPa [1].
- The clay brick in the model has a compressive strength of 15 MPa which is identical to the compressive strength of the clay brick of Al-Malwiya that was evaluated as 15 MPa [1].
- Since the model gives the least value for the masonry modulus of elasticity, among the other models, then it is reasonable to adopt this model conservatively, as the current study is dealing with valuable heritage minaret.

Therefore, the masonry modulus of elasticity in current study is determined from the empirical formula $E_m = 85\ f_m$ in Table 2, which leads to the value of masonry modulus of elasticity of Al-Malwiya to be equals $85 \times 15 = 1275$ MPa.

The value 1275 MPa is considered as a low-value compared with those of cement-mortar based masonries, which can be evidenced by looking at the common empirical formulas presented in Table 1 and at the first formula (M6 mortar) in Table 2. Also, this value is relatively low compared with the values which can be achieved by using the empirical model $E_m = 130\ f_m$ of the hydraulic lime mortars NHL5 and NHL3.5 in Table 2. However, the relatively low-value of the masonry modulus of elasticity can be demonstrated as a result of the environmental factors and the other weakening factors that affect the strength behavior and the mechanical characteristics of this historic minaret along about 1200 years.

For a rough comparison, the estimated value of 1275 MPa falls in the range of the values of masonry modulus of elasticity that reported by Lumantarna et al. [9] for eight masonries, in New Zealand, constructed between 1884 and 1930 s, which were between 388 MPa and 4286 MPa. Furthermore, the masonry has generally low strength compared with its units due to the weakness in interaction bonding between the units and the mortar [16], which leads necessarily to relatively low values of the masonry modulus of elasticity.

3.2 The masonry shear modulus and Poisson's ratio

As stated in the previous section, the shear modulus G_m in this study is evaluated according to the empirical formula presented in Eurocode 6 [6] and MSJC [8], $G_m = 0.4\ E_m$, which is widely used in absence of experimental tests. Therefore, based on the estimated modulus of elasticity $E_m = 1275$ MPa, the value of shear modulus is evaluated as 510 MPa, which represents the ratio 0.4 times 1275 MPa. The indications of this value are similar to those of modulus of elasticity since the shear modulus represents a constant ratio of modulus of elasticity. Regarding the value of masonry Poisson's ratio, this value is adopted to be 0.25 as aforementioned in the previous section.

3.3 Mass density of the masonry

The mass density of the masonry of Al-Malwiya is estimated by using the following equation, which represents the summation of the mass density contributions for each element (bricks and mortar),

$$D_m = D_b \cdot R_b + D_j \cdot R_j \,, \tag{3}$$

where:
D_m - mass density of the masonry [kg/m^3],
D_b - mass density of the bricks [kg/m^3],
D_j - mass density of the mortar in the joints [kg/m^3],
R_b - volumetric ratio of the bricks (volume of the bricks per a unit volume of the masonry),
R_j - volumetric ratio of the mortar in the joints (volume of the mortar per a unit volume of the masonry).

The mass density and the dimensions of the brick for the masonry of Al-Malwiya, are 1507 kg/m^3 and 27 cm × 27 cm × 7 cm respectively [1]. Therefore, the value of D_b in Eq. (3) is

$$D_b = 1507 \text{ kg/m}^3 . \quad (4)$$

The mass density of the mortar is computed as the mean value for the mass densities of the mortar samples after conducting the experimental tests as shown in Table 3. Therefore, the mass density of the mortar D_j is determined as

$$D_j = 1385 \text{ kg/m}^3 . \quad (5)$$

Table 3: Details of computing the mass density of the historic mortar.

Sample	Mass [g]	Volume [cm^3]	Mass density [g/cm^3]
1	23.7	17.5	1.354
2	24.7	18.0	1.372
3	21.3	15.0	1.420
4	32.8	23.0	1.426
5	27.9	20.0	1.395
6	14.8	11.0	1.345
Mean value in [g/cm^3]			1.385
Mean value in [kg/m^3]			1385

To compute the volumetric ratios for the bricks and mortar, each brick is assumed to take a thickness of one half of the mortar width for each of its faces, this leads to the dimensions of the brick with its mortar to be 28 cm × 28 cm × 8 cm and its volume becomes

$$28 \text{ cm} \times 28 \text{ cm} \times 8 \text{ cm} = 6272 \text{ cm}^3 . \quad (6)$$

But the volume of one brick is

$$27 \text{ cm} \times 27 \text{ cm} \times 7 \text{ cm} = 5103 \text{ cm}^3 . \quad (7)$$

Thus, the volumetric ratio of the brick unit R_b is obtained from dividing the volume of the brick, from Eq. (7), by the volume of brick with its mortar, from Eq. (6), to get

$$R_b = 0.814, \quad (8)$$

and the volumetric ratio of the mortar R_j is computed by subtracting the volumetric ratio of the brick R_b, which obtained from Eq. (8), from the unit volume of the masonry to get

$$R_j = 0.186. \quad (9)$$

Finally, the mass density of the masonry of Al-Malwiya D_m is determined by substituting the values obtained from equations 4, 5, 8, and 9 into Eq. (3) to get

$$D_m = 1484.3 \text{ kg/m}^3 . \quad (10)$$

The value 1484.3 kg/m^3 can be converted to a weight density in order to compute the self-weight of the masonry of Al-Malwiya which is required in structural analysis.

4 Conclusions

Based on the adopted approach of the present study, the following conclusions are drawn:

- There are many approaches that can be used in structural studies of the heritage buildings due to complexity in dealing with such buildings. Choosing the appropriate approach depends on the availability of information and the limitations of each procedure as well as the required level of the conservation.
- The values of the masonry modulus of elasticity and the masonry shear modulus for Al-Malwiya masonry are conservatively estimated as 1275 MPa and 510 MPa respectively. These values may be considered to be relatively small values compared with the those of new masonries constructed with normal strength of lime-mortar, but these values are reasonable for a historic masonry that have been affected by environmental and weakening factors for about 1200 years.
- The estimated value of Poisson's ratio for Al-Malwiya masonry is 0.25, and the estimated mass density is 1484.3 kg/m^3.
- Further investigations are recommended by using other approaches in order to establish complete information for the characteristics of this minaret and its constituent materials.

Acknowledgments

The author wishes to acknowledge the staff of Al-Malwiya site office, especially Mr. Khalid Qaddoori, Mr. Khaldoon Khalil, and Mr. Wisam Hameed for their valuable assistance in the research. Also, the author would like to thank the Faculty of Engineering at the University of Samarra for its support in communication with Al-Malwiya site office.

References

[1] HUSAIN, M. A. – HAMAD, S. Y. – FARAJ, M. M. – HASAN, Z. H.: Prediction of compressive strength of the masonry of Al-Malwiya historic minaret in Samarra. Materials Today. Proceedings. Vol. 42, Part 5, Jan. 2021, pp. 2314–2319, doi: 10.1016/j.matpr.2020.12.321.
[2] ASTM C1314 - 14: Standard Test Method for Compressive Strength of Masonry Prisms. ASTM International, Pennsylvania, United States, 2014.
[3] PAULAY, T. – PRIESTLY, M. J. N.: Seismic Design of Reinforced Concrete and Masonry Buildings. Hoboken, NJ, USA: John Wiley & Sons, Inc., 1992.
[4] DRYDALE, R. G. – HAMID, A. A. – BAKER, R.: Masonry structures-behaviour and design. Pract. Hall, Ennglewood Cliffs, New Jersey, 1994.
[5] CSA S304.1: Design of masonry structures. Canadian Standards Association, Ontario, Canada, 2004.
[6] CEN, Eurocode 6: Design of masonry structures. General rules for reinforced and unreinforced masonry structures. European Committee for Standardization, Brussels, Belgium, 2005.
[7] KAUSHIK, H. B. – RAI, D. C. – JAIN, S. K.: Stress-Strain Characteristics of Clay Brick Masonry under Uniaxial Compression. J. Mater. Civ. Eng., Vol. 19, No. 9, 2007, pp. 728–739, doi:10.1061/(asce) 0899-1561(2007)19:9(728).
[8] MSJC, Masonry Standards Joint Committee: Building code requirements for masonry structures, American Concrete Institute, Structural Engineering Institute of the American Society of Civil Engineers, The Masonry Society. Detroit, 2008.
[9] LUMANTARNA, R. – BIGGS, D. T. – INGHAM, J. M.: Uniaxial Compressive Strength and Stiffness of Field-Extracted and Laboratory-Constructed Masonry Prisms. J. Mater. Civ. Eng., Vol. 26, No. 4, 2014, pp. 567–575, doi: 10.1061/(asce)mt.1943-5533.0000731.
[10] COSTIGAN, A. – PAVIA, S. – KINNANE, O.: An experimental evaluation of prediction models for the mechanical behavior of unreinforced, lime-mortar masonry under compression. J. Build. Eng., Vol. 4, No. November 2015, pp. 283–294, doi: 10.1016/j.jobe.2015.10.001.
[11] GUADAGNUOLO, M. – AURILIO, M. – BASILE, A. – FAELLA, G.: Modulus of Elasticity and Compressive Strength of Tuff Masonry: Results of a Wide Set of Flat-Jack Tests. Buildings, Vol. 10, No. 5. 2020, doi: 10.3390/buildings10050084.
[12] BINDA, L. – SAISI, A.: Application of NDTs to the diagnosis of historic structures. NDTCE'09. Non-Destructive Test. Civ. Eng. Nantes, 2009.
[13] BOSILJKOV, V. Z. – TOTOEV, Y. Z. – NICHOLS, J. M.: Shear modulus and stiffness of brickwork masonry: An experimental perspective. Struct. Eng. Mech., Vol. 20, No. 1, May 2005, pp. 21–43, doi: 10.12989/sem.2005.20.1.021.

[14] RADOVANOVIC, Z. – SINDIC, R. – DIMOVSKA, S. – SERDAR, N. – VATIN, N. – MURGUL, V.: The mechanical properties of masonry walls - Analysis of the test results. Procedia Eng., Vol. 117, No. 1, 2015, pp. 865–873, doi: 10.1016/j.proeng.2015.08.155.
[15] CAVALERI, L. – PAPIA, M. – NACALUSO, G. – DI TRAPANI, F. – COLAJANNI, P.: Definition of diagonal Poisson's ratio and elastic modulus for infill masonry walls. Mater. Struct. Constr., Vol. 47, No. 1–2, Jan. 2014, pp. 239–262, doi: 10.1617/s11527-013-0058-9.
[16] DAWOOD, A. O. – MUSSA, F. I. – AL KHAZRAJI, H. – ABD, H. A. – YASSER, M. M.: Investigation of Compressive Strength of Straw Reinforced Unfired Clay Bricks for Sustainable Building Comstruction. Civil and Environmental Engineering, Vol. 17, Iss.1, 2021, pp. 150-163, doi:10.2478/ cee-2021-0016.