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Properties of Uniaxially Compressed Clay Brick Masonry with Respect to Stress and Strain

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Abstract:

Various laboratory studies have been conducted to study the unreinforced masonry's and its constituents' properties, including its uniaxial monotonic compressive stress-strain behavior and other features. The extensive experimental study yielded nonlinear stress-strain curves for masonry, mortar, and bricks. Additionally, the masonry stress-strain curves had six "control points" that could be used to define the performance limit states of the material or member. In order to facilitate analysis and design processes, a straightforward analytical approach for producing masonry stress-strain curves has been suggested, which makes use of linear regression analysis. Brick and mortar compressive strengths are the only input data needed by the model. These values are readily accessible in codes and may be acquired experimentally with relative ease. The modulus of elasticity of masonry, mortar, and bricks may be calculated from their respective compressive strengths using simple equations. When comparing masonry stress-strain curves to those of bricks and mortar, it was found that the former does not always fall in the middle, even when the latter is stronger and stiffer.

Introduction

For numerous reasons, including their cheap cost, high sound and heat insulation, ease of availability, and the availability of both the material and competent labor in the area, masonry walls are a common choice for building construction. Due to a lack of controlled experimental tests and substantial geographical variation in material properties, the material properties and constitutive relationships of masonry and its constituents, i.e., bricks and mortar, are not readily available for mathematical modeling of structures with masonry walls. The local hand-molded burned clay solid bricks, mortar, and unreinforced masonry prisms are the focus of this work, along with their uniaxial monotonic compressive stress-strain behavior and other features.

Compressive Behavior of Masonry

Masonry is typically a nonelastic, nonhomogeneous, and aniso-tropic material composed of two materials of quite different prop-erties: stiffer bricks and relatively softer mortar. Under lateral loads, masonry does not behave elastically even in the range of small deformations. Masonry is very weak in tension because it is composed of two different materials distributed at regular inter-vals and the bond between them is weak. Therefore, masonry is

normally provided and expected to resist only the compressive forces. As shown in Figs. 1(a and b), during compression of ma-sonry prisms constructed with stronger and stiffer bricks, mortar of the bed joint has a tendency to expand laterally more than the bricks because of lesser stiffness. However, mortar is confined laterally at the brick–mortar interface by the bricks because of the bond between them; therefore, shear stresses at the brick-mortar interface result in an internal state of stress which consists of triaxial compression in mortar and bilateral tension coupled with axial compression in bricks. This state of stress initiates vertical splitting cracks in bricks that lead to the failure of the prisms (McNary and Abrams 1985; Atkinson and Noland 1983; Drysdale et al. 1994).

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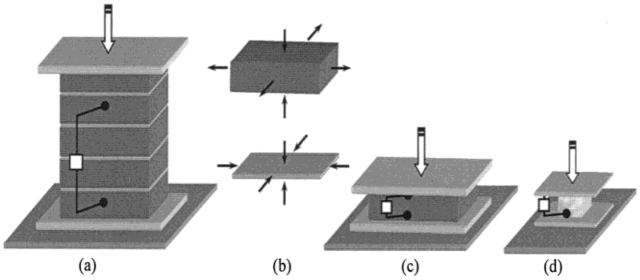

Fig. 1. Test setup for different specimens: (a) masonry prism; (b)

Most people assume that masonry, being a combination of bricks and mortar, would have a strength and stiffness somewhere in the middle. According to Dayaratnam (1987) and Sarangapani et al. (2002), bricks from southern India are highly weak and soft, therefore this may be the situation when one portion of the masonry—mortar or bricks—is much weaker and softer than the other. Sarangapani et al. (2002) found that axial compression with lateral tension in the mortar joints of masonry prism and triaxial compression in the bricks themselves were caused by soft bricks with a modulus of elasticity of around 500 MPa. This goes against what is often expected of masonry built with hard bricks and a softer mortar.

Masonry prisms built with a mixture of various mortar grades and very soft bricks (modulus of elasticity ~500 MPa) were subjected to a battery of tests by Sarangapani et al. (2005). For brick-mortar masonry that is both soft and stiff, the compressive strength of the masonry grows in relation to the bond strength, which in turn grows in relation to the mortar strength and other variables. In 2004, Ewing and Kowalsky conducted tests on three separate, unconfined, single-wythe clay brick masonry prisms made of a single type of brick and mortar grade. They then proposed four performance limit states, which correspond to 75 and 90% of the prism's compressive strength on the stress-strain curve's rising branch, and 50 and 20% of the prism's compressive strength on the falling branch. The stress-strain curve of ma-sonry may be properly predicted using the "modified" Kent-Park model that Priestley and Elder (1983) suggested for concrete masonry. Further support for using the "modified" Kent-Park model (Priestley and Elder 1983) in the context of unconfined masonry came from Paulay and Priestley (1992). The model is made up of three main parts:

The following equations define a parabolic rising curve, a linear descending branch, and a final hori-zontal plateau of constant stress (at 20% of masonry prism strength).

An analytical model describing the failure criteria of masonry prisms was validated by McNary and Abrams (1985) through a battery of uniaxial, biaxial, and triaxial tests performed on clay bricks, mortar, and masonry. This model takes into account the nonlinear behavior of confined mortar (between bricks) and splitting strengths of bricks. After investigation, it was determined that the masonry prisms collapsed due to the mortar-induced lateral tension cracking of the bricks. The analytical determination of the compressive strengths of ma-sonry, bricks, and mortar is dependent on their compressive and tensile strengths; many relations were developed for this purpose. The linear relationship between the masonry prism strength and the compressive strength of bricks was demonstrated by Bennett et al. (1997) through regression analysis of multiple experimental results on low structural clay tiles. To provide a conservative estimate, the prism strength for loading perpendicular to the bed joint is three-tenths of the brick compressive strength. Since the approach does not take the strength of the mortar into account, it is possible that the estimated strength of the masonry prisms will be overestimated. Additionally, it was suggested that the elastic modulus and prism strength of brickwork are linearly related.

Based on previous experimental research, Sawko and Rouf (1984) offered an analytical method for calculating the axial and bending stiffness of masonry walls by taking into account the parabolic variation of stress-strain curves for masonry under compression. The authors did not provide a technique for estimating the peak strain, but they did indicate that the parabolic variation should continue in the descending half until it reaches 1.5 times the peak strain equivalent to prism strength.

The analytical relationships proposed by Grimm (1975), Paulay and Priestley (1992), and Binda et al. (1988) for the purpose of estimating the compressive and tensile strengths of bricks and mortar, among other factors, as well as the deformation characteristics of masonry, are dependent on experimental data.

Numerous studies have examined masonry and its components, but only a handful have proposed straightforward analytical relationships for determining masonry's compressive strength and deformation properties (Grimm 1975; McNary and Abrams 1985; Paulay and Priestley 1992; Bennett et al. 1997). In addition, there are a handful of mathematical models that can display compressive stress-strain curves for

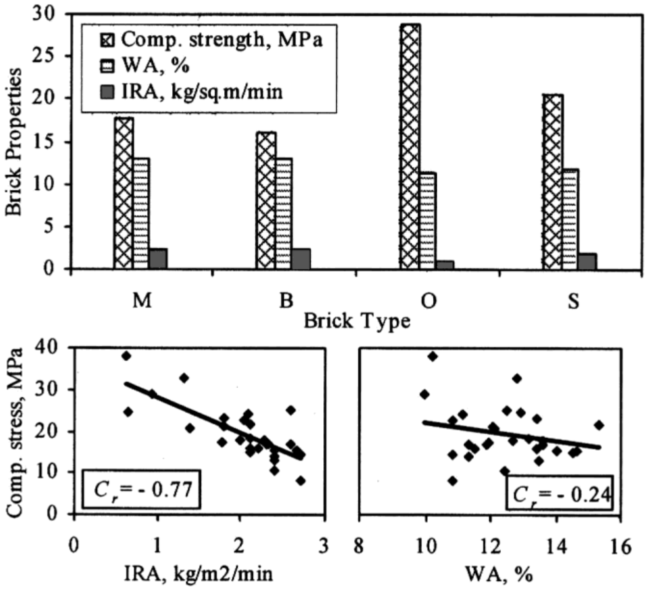

Fig. 2. Effect of water absorption and initial rate of absorption on compressive strength of bricks (C_r=correlation coefficient)

Experimental Program

Various brick and mortar combinations, as well as masonry prisms, were subjected to a battery of experiments designed to measure the uniaxial compressive stress-strain curves. The four local brick makers utilized were M, B, S, and O. The bricks were about 230 mm long, 110 mm wide, and 75 mm tall. In order to determine the bricks' quality, IRA and WA tests were conducted on brick units. A 250 kN load with a ±125 mm displacement was applied vertically to the top of masonry prisms and mortar cubes, subjecting them to a strain-controlled displacement loading that increased monotonically. motor control system servo-hydraulic actuator with a high capacity. Nevertheless, brick units were subjected to stress-controlled loading in a universal testing equipment with a capacity of 2,000 kN. The displacement response during the experiments was recorded by instrumenting each specimen with an Epsilon extensom-eter. The research used two different extensometer sizes: one for prism testing, with a 200 nm gauge length and ±12 mm peak displacement capacity, and another for brick and mortar cube testing, with a 25 mm gauge length and ±5 mm peak displacement capacity. The displacement in masonry prisms was measured across three mortar joints, as seen in Figure 1(a), so order to account for the deformations in both the bricks and the mortar joints. The displacements were documented on the faces of the brick units and mortar cubes, as seen in Figures 1(c and d). In every test, a computer-based data collecting system immediately captured the vertical load and displacement values at specific points. Stress-strain curves reported in the paper are arrived at by the double averaging method, i.e., averaged strain values are plotted on the abscissa against the predetermined stress values on the ordinate (control points), which are also averaged across different specimens. The highest and lowest values in a set of data are not considered while averaging that particular set of data. Modulus of elasticity is calculated from stress-strain curves by measuring the slope of a secant between ordinates corresponding to 5 and 33% of the ultimate strength of the specimens (MSJC 2002).

Tests for WA and IRA of Bricks

Total water absorption capacity of the brick material is given by the WA test. The absorption of moisture by capillary action in the bricks produces a *suction* effect that draws water from mortar and this characteristic is defined by IRA. The rate of absorption can have an important effect on the interaction between freshly laid mortar and the brick units. IRA is measured in order to assist in mortar selection and material handling in the construction pro-cess. It is measured in terms of mass of water absorbed (per minute) by the brick material per unit area of brick immersed in about 3 mm deep water, which is kept constant by adding water during the test, as per ASTM C 67-00 (ASTM 2001c). IS 3495 (IS 1992b) was used to perform a WA test whose provisions are similar to those given in ASTM C 67-00 (ASTM 2001c).

Fig. 2 shows the variation in compressive strength of bricks (f_b) with IRA and WA and Table 1 gives the corresponding sta-tistics. WA was found to vary from 11 to 13% [mean 12.3%, coefficient of variation (COV) 0.13] and IRA varied from 0.97 to 2.42 kg/m^2/min (mean 1.9 kg/m^2/min, COV 0.34); lower IRA values were found for bricks with higher f_b. In the present study, a much better correlation was observed between IRA and f_b (correlation coefficient −0.77) than that between WA and f_b (cor-relation coefficient −0.24). Too high or too low an IRA is detri-mental to achieving a good initial and final bond between brick and mortar, which not only affects the masonry flexural strength, but also its water tightness and durability. It was observed by Drysdale et al. (1994) that if IRA is less than 0.25 kg/ m^2 / min, which is a case for low absorption or low-suction bricks, then such bricks may tend to flow on mortar, particularly if the bricks are damp. On the other hand, for highly porous and absorptive bricks (IRA$>$ 1.5 kg/ m^2 / min), a poor brick–mortar bond may result for thin mortar joints with less water–cement ratio because of rapid suction of water in mortar by bricks.

Stress-Strain Curves for Bricks

The tests were performed in accordance with ASTM C 67-00 (ASTM 2001c) and IS 3495 (IS 1992a). The experimental setup

Table 1. Summary of Test Results for Brick Units

Brick type	f_b (MPa)	Failure strain	E_b (MPa)	WA (%)	IRA (kg/ m^2 / min)
M (10 specimens)	17.7 [0.23][a]	0.0072 [0.18]	5,300 [0.15]	12.9 [0.11]	2.26 [0.12]
B (10 specimens)	16.1 [0.08]	0.0060 [0.19]	5,030 [0.34]	13.0 [0.11]	2.42 [0.09]
O (10 specimens)	28.9 [0.23]	0.0070 [0.39]	7,516 [0.26]	11.4 [0.21]	0.97 [0.34]
S (10 specimens)	20.6 [0.17]	0.0057 [0.28]	6,534 [0.10]	11.8 [0.05]	1.89 [0.24]
Average (40 specimens)	20.8 [0.33]	0.0065 [0.34]	6,095 [0.29]	12.3 [0.13]	1.90 [0.34]

[a] Figures in [ ] brackets indicate coefficient of variation.

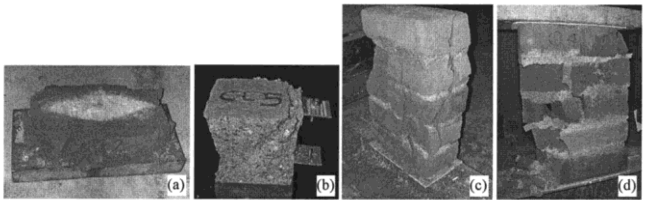

Fig. 3. Typical failure modes of: (a) brick units; (b) mortar cubes; and (c), (d) masonry prisms

Figures 1(c) and 3(a) show the testing procedure and the typical crushing failure of bricks, respectively. By averaging the stress-strain data from 10 samples of each brick type, the stress-strain curves for the four kinds are shown in Figure 4(a). The bricks exhibited linear behavior until they reached about one-third of the ultimate failure stress, at which point their behavior turned significantly nonlinear. Furthermore, Figure 4(a) displays the mean stress-strain curve for each of the brick varieties used in the research. Table 1 provides a synopsis of the data, which include fb, failure stresses, and Eb (modulus of elasticity). Mean fb values ranged from 16.1 to 28.9 MPa (mean 20.8 MPa, COV 0.33) for the various bricks used in the investigation. The average strains at failure that were documented in

Eb ranged from 5,000 to 7,500 MPa (mean 6,095 MPa, COV 0.29) while the brick specimens showed a wide range of values from 0.0057 to 0.0072 (mean 0.0065, COV 0.34). In Fig. 5(a), we can see that Eb fluctuates between 150 and 500 times fb as a function of fb. To get the mean value of Eb, one may use

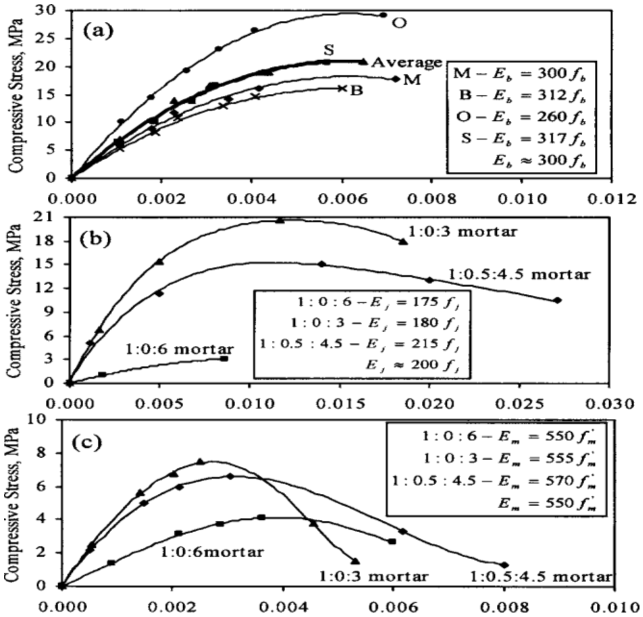

Fig. 4. Compressive stress-strain curves for: (a) brick units; (b) mortar cubes; and (c) masonry prisms

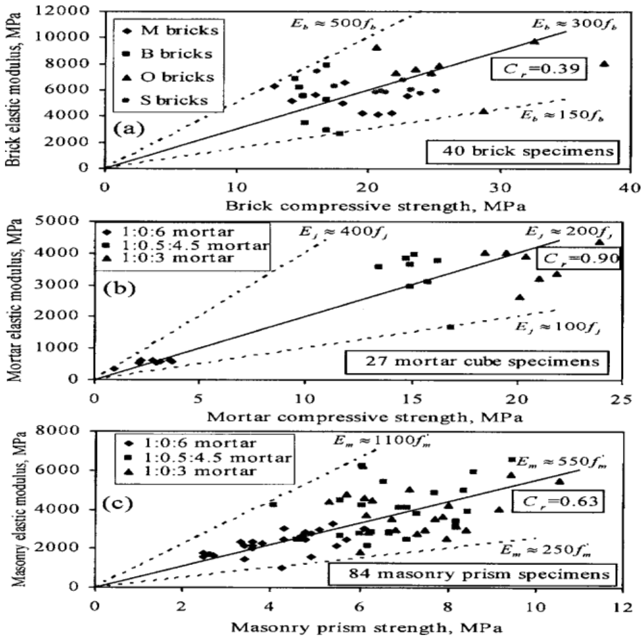

Fig. 5. Variation of modulus of elasticity of: (a) bricks; (b) mortar; and (c) masonry with corresponding compressive strengths

Conclusions

Creating stress-strain curves and conducting experimental investigations into the compressive behavior of masonry and its components were the primary goals of the project. The study also examined the relationship between the strengths of bricks, mortar, and masonry, as well as the impacts of various variables on these strengths and ductility, including water absorption, initial rate of absorption, and the addition of lime to the mortar.

The correlation between IRA and brick compressive strength was stronger than that between WA and brick strength. Bricks with lower IRA values showed significantly greater compressive strengths. There was a much stronger connection between IRA and compressive strength (−0.77) compared to WA and compressive strength (−0.24). Hence, the national rules need to mandate IRA testing for bricks. We propose a simple relation that estimates the modulus of elasticity of masonry at 550 times its compressive strength, mortar at 200 times its compressive strength, and bricks at 300 times their compressive strengths. As the compressive strengths of bricks and mortar increased, so did the masonry prism's compressive strength. The strength of the brickwork was increased, although it was more noticeable in the case of the weaker mortar. Therefore, using a higher strength mortar than required is unlikely to produce higher strength masonry.

Stress-strain curves of masonry constructed with bricks and mortar of comparable strengths and stiffness was observed to lie below the stress-strain curves of both bricks and mortar, which is not in accordance with the generally accepted compressive behav-ior of masonry. Hence, in order to create a generic model for the compressive behavior of masonry, more experimental research using various mixes of brick kinds and mortar grades is necessary.

Despite having a compressive strength that is about 35% lower than strong mortar, lime-based mortar exhibited superior compressive behavior due to its increased ductility, with a failure strain that was approximately 45% higher. The compressive behavior of lime mortar masonry was much better than that of limeless mortar masonry for the same reasons; failure strain was about 50% higher and prism strength was only approximately 13% lower than that of prisms with strong mortar. Adding lime in mortar is a very old practice in many parts of the world, including India;

however some national codes, e.g., IS1905 (IS 1987) and Euro-code6 (CEN 1996), allow the use of limeless mortars; which this research indicates may not be a good construction practice.

There were six major occurrences that were seen experimentally, each indicating compressive stresses in brickwork and the related strains. These six points on the compressive stress-strain curves of masonry serve as control points. The control points can also be used as performance limit states for masonry material and member. Based on these control points, an analytical model was developed by regression analysis of the experimental data to plot the masonry stress-strain curves, which follow a combination of parabolic and linear variation. With only two parameters—the compressive strength of the bricks and the mortar—the analytical model is very straightforward. When compared to other analytical and experimental studies published in the literature, the model provides reasonably accurate stress-strain curve estimations. This makes it a useful tool for masonry element analysis and design processes. Conclusions made in the present study may change based on different combinations of ce-ment, lime, sand, and water used in brickwork.

References

"ASTM" (2001a). "Test procedure for hydraulic cement mortar compressive strength (using 2-inch or 50-mm cube specimens)" American Society for Testing and Materials (ASTM) publication C 109/C 109M-99, 4th edition, Philadelphia, 2001 (2001b). "Constant test procedure for modulus of compression of

translucent prisms. Standard Test Methods and Criteria for the Construction Industry (ASTMC 1314-00a), Fourth Edition, Philadelphia, ASTM, 2013. italics added. "Procedures for the systematic examination of structural clay tile and brick samples." Publication: ASTM-C67-00, Fourth Edition, Philadelphia, Methods and requirements for testing masonry in the construction sector.
The authors of the 1983 work are Atkinson and Noland. "Theory of brick masonry failure in compression," Volume 3, Issue 5, Pages 5–17, Third Canadian Masonry Symposium, Edmonton, Alberta, Canada.
In 1997, Bennett, Boyd, and Flanagan published a work. Journal of Structural Engineering, 123(7), 920-926, 2016.
In 1988, Binda, Fontana, and Frigerio published a paper. "Mechanical behaviour of brick masonries derived from unit and mortar characteristics." Proc., 8th Int. Brick and Block Masonry Conf., Vol. 1, Dublin, Ireland, 205–216.
Canadian Standards Association (CSA). (2004). Design of masonry structures, S304.1, Ontario, Canada.
Dayaratnam, P. (1987). Brick and reinforced brick structures, Oxford and IBH, New Delhi, India.
Drysdale, R. G., Hamid, A. A., and Baker, L. R. (1994). Masonry struc-tures: Behaviour and design, Prentice-Hall, Englewood Cliffs, N.J.
European Committee of Standardization (CEN). (1996). "Design of masonry structures. Part 1-1: General rules for buildings—Reinforced and unreinforced masonry." ENV 1996-1-1, Eurocode 6, Brussels, Belgium.
Ewing, B. D., and Kowalsky, M. J. (2004). "Compressive behavior of unconfined and confined clay brick masonry." J. Struct. Eng., 130(4), 650–661.

Federal Emergency Management Agency (FEMA). (1999). Evaluation of earthquake damaged concrete and masonry wall buildings, basic pro-cedures manual, ATC-43, FEMA 306, Applied Technology Council, Calif.
Grimm, C. T. (1975). "Strength and related properties of brick masonry." J. Struct. Div., 101(1), 217–232.
Hendry, A. W. (1998). Structural masonry, 2nd Ed., Macmillan, London. International Code Council. (2003). International building code, Va.
Indian Standards (IS). (1987). Indian standard code of practice for structural use of unreinforced masonry, IS1905, 3rd Rev., Bureau of Indian Standards, New Delhi, India.
Indian Standards (IS). (1992a). Indian standard methods of test of burn clay building bricks—Part 1: Determination of compressive strength, IS 3495, 3rd Rev., Bureau of Indian Standards, New Delhi, India.
Indian Standards (IS). (1992b). Indian standard methods of test of burn clay building bricks—Part 2: Determination of water absorption, IS 3495, 3rd Rev., Bureau of Indian Standards, New Delhi, India.
Indian Standards (IS). (1995). Indian standard code of practice for preparation and use of masonry mortars, IS2250, 5th Rev., Bureau of Indian Standards, New Delhi, India.
Masonry Standards Joint Committee (MSJC). (2002). Building code requirements for masonry structures, ACI 530-02/ASCE 5-02/TMS 402-02, American Concrete Institute, Structural Engineering Institute of the American Society of Civil Engineers, The Masonry Society, Detroit.