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Properties of Brick Masonry for FE modeling

Narayanan S P[1], Sirajuddin M[2]
[1](Department of Civil Engineering, Universiti Teknologi PETRONAS, Malaysia)
[2](Department of Civil Engineering, T.K.M College of Engineering, India)

Abstract: - Brick masonry exhibits distinct directional properties due to the mortar joints, which act as planes of weakness, resulting in brick masonry structures showing complex and non-linear mechanical behaviour. The analysis of mechanical behavior of brick masonry still remains a true challenge. Properties of brick masonry components are important in the FEM analysis of masonry structures. Three varieties of brick and three mix proportion of mortar were considered for experiments. Compressive strength, water absorption, Modulus of elasticity and Poisson ratio of bricks and Compressive strength, Modulus of elasticity, Poisson ratio and density of different mortars were determined. The results were compared and discussed and suitable values for non – linear FE analysis of masonry buildings were recommended.

Keywords: - *masonry structure; finite element modeling, mortar, mechanical behavior, experimental investigation*

I. INTRODUCTION

Masonry is one of the oldest building materials. Brick masonry using mortar has proved as a successful technique due to its simplicity and durability of construction. Such structures are very weak in bending and shear due to lateral loads. Damages due to earthquake are increasing. Strengthening of masonry structures against it is vital. For examining this finite element software is used, which requires knowledge of basic mechanical properties of brick masonry components. Masonry is composed of masonry units and mortar. Brick shows nonlinear material behavior and different directional properties. This work examines the literature on properties of brick/blocks and mortar and also reports an experimental work on determining the properties of brick and mortar used for construction in Kollam, Kerala. Main masonry codes are ACI 530-02 [1], IBC 2000 [2], NZS 4230:1: 1990 [3], Eurocode 6 [4] and IS 1905-1987 [5]. Design philosophies include Empirical (ACI 530-02 [1]), Allowable Stress (ACI 530 [1] and IS 1905 [5]) and Limit State Design (ACI 530-2 [1], IBC 2000 [2], NZS 4230:1: 1990 [3]. In each philosophy, equations are available to evaluate strength values.

II. LITERATURE REVIEW

In traditional design of masonry based on rules of thumb and empirical formulae, thickness of the walls is based on static dead and live loads. This required only compressive strength (CS) of brick. Sophisticated numerical tools are being tried [6]. The lack of information on characteristic properties of masonry components is a drawback. Bricks used in western countries have CS in the range 15-150 MPa and modulus of elasticity (MOE) between 3500 and 34000 MPa [7] [8]. Australian bricks have MOE 7000 to 12000 MPa and PR between 0.12 and 0.29 [9]. Nichols and Totoev [10] determined the static and dynamic MOE using quasi static methods and non-destructive methods respectively. Pressed red clay bricks had E=14000MPa , ν=0.22 and density ρ=2070 to 2320 kg/m^3 whereas other brick types had the following values: pressed clay biscuit (E=10000 MPa; ν=0.29, ρ=2220 to 2270 kg/m^3), Pressed clay brown (E=7000 MPa; ν=0.21, ρ=2130 to 2170 kg/m^3), calcium silicate (E=6000; ν=0.17, ρ=1740 to 1810 kg/m^3) and concrete (E=14000; ν=0.33, ρ= 2010 to 2190 kg/m^3). Studies on bricks in India show relatively lower strength values of 2.5 to 20MPa and MOE of 300 – 16000MPa [11] [12]. MOE of cement mortar (1:6) adopted commonly for brick masonry all over India is 10 to 15 times higher than that of the bricks. Gumaste et al [11] noted that the strength of brick masonry is in the range of 25% - 50% of the brick strength and generally the brick masonry strength increases with increase in brick / mortar strength. Studies also indicate low masonry efficiency for higher brick strength [13] [14]. Gumaste et al [11]

studied table mounted and higher strength wire cut bricks of Bangalore (India) with different combinations of high and low brick strength and soft and stiff mortar . Kaushik et al [15] [16] reported the compressive stress – strain relationship for masonry by testing 84 masonry prisms using bricks from 4 different manufacturers and 3 mortar grades. Based on the experimental observations, the MOE of masonry was found to vary between 250 and 1100 times the prism strength of masonry. An average value of 550 times the prism strength was proposed. The tests results may be valid for North Indian bricks. In EC6 [4], the characteristic CS of masonry is determined using equation (1).

$$f_b = K f_b^{\alpha} f_m^{\beta} \quad (1)$$

where K= a constant; α, β=constants; fb=normalized mean CS of units in the direction of applied action effort in N/mm^2; fm = CS of mortar in N/mm^2.

The characteristic shear strength of masonry may be obtained directly from tests using [17] [18] or using equation (2)

$$f_{vk} = f_{vk0} + 0.4\sigma_d \quad (2)$$

but not greater than 0.065fb or fvlt where fvk0 is characteristic initial shear strength, under zero compressive stress determined using EN 1052-3 [19] or tabulated values. fvlt is limit value to fvk.

The characteristic flexural strength of masonry having plane of failure parallel to bed joints and perpendicular to bed joints may be determined by direct tests (using EN 1052-2) or evaluated from data on units and mortar. In the absence of test data, tabulated values from EC6 may be used. EC6 recommends formulae for short term secant MOE of masonry (equation (3)) and long term modulus is determined from short term secant value applying reduction factor for creep (equation (4).

Short Term secant modulus $E = K_E f_k$ (3)

where KE=1000.g

Long term modulus $E_{longTerm} = \dfrac{E}{1+\phi}$ (4)

where Φ=final creep coefficient.

UBC recommends MOE of masonry in compression be determined using equation (5) [20]

$$E_m = \frac{(1+\gamma_t)}{\left(1+\dfrac{\gamma_t}{\gamma_m}\right)} E_b \quad (5)$$

where γt is the thickness ratio, γm is the ratio of modulus and Eb modulus of bricks assumed to be $37000N/mm^2$ [21]. The shear modulus G may be taken as 40% of E.

In IS 1905 [5], there are two methods to find the basic CS. Unit strength method utilizes tabulated values of basic CS depending on mortar type and strength of units. Permissible CS is obtained from basic CS by multiplying with stress reduction factor, area reduction factor and shape modification factor. Alternately prism test method is used. In-plane permissible shear stress Fv shall not exceed 0.5Mpa,.1 + 0.2fd, and $0.125\sqrt{f_v}$ where fd is the compressive stress due to dead loads in N/mm^2. MOE for clay and concrete masonry is given by $E_m = 550\, f_m$. (6)

Alternately it can be determined by testing. The shear modulus is taken as 0.4 times the MOE without any experimental evidence to support it. Properties of brick and mortar for FEM modeling of masonry structures in Kollam in Kerala are not available. These are experimentally determined and compared with brick elsewhere. The objective of this experimental investigation is to find out the basic material properties of brick units and mortar units such as PR, MOE and CS.

Studies by the authors showed that damages occurred during earthquakes to masonry buildings in Kerala. The complex nature of buildings indicated the need for FE analysis [22][23][24]. Compressive strengths and other properties for different varieties of bricks and blocks were evaluated and compared [25]. This study evaluates further the properties of bricks required for FE analysis. The application of these properties for FE analysis has been reported in [26].

III. EXPERIMENTAL INVESTIGATIONS

3.1 Tests on Brick Units

Three varieties of brick units (2 types of wire cut bricks (WCB1 and 2) and one type of country burnt brick (CBB) from different kilns of Kollam were chosen. CS and water absorption (WA) tests were carried out as per IS 3495 [27]. CS of masonry primarily depends on strength of individual brick units. CS of brick depends up on composition of clay, method of brick manufacturing and degree of firing. Brick units were tested in dry condition. CS and WA indicate the general quality of the material. WA gives the durability of brick. MOE was determined by using stress-strain values from axial compression of individual brick units. MOE and PR brick specimens consisted of bricks cut such that, the length to least lateral dimension ratio is between 2 to 2.3 [28], 2003). Size of the brick specimens for MOE and PR were 141×101×70mm, 142×99×70mm etc. Brick units were kept in compression testing machine in vertical position. Steel plates were placed at top and bottom face of the brick specimen, and load was applied gradually in equal increments. Five deflection dial gauges (DG) were used for measuring deformations. DGs had least count of 0.01mm and maximum deformation of 25mm.
The sides of the brick specimens were then rubbed along a rough surface to get a smooth surface finish. The Individual units of bricks were subjected to uniaxial compression in a compression testing machine of capacity 5 T. Brick units were kept in compression testing machine in vertical position. Steel plates were placed at top and bottom face of the brick specimen, and load was applied gradually in equal increments. Five deflection dial gauges were used for measuring deformations. The dial gauges had least count of 0.01mm and maximum deformation of 25mm. The positions of the dial gauges are shown in figure. Small Perspex sheets were fixed at the location where deformation was to be measured, so that the spindle of dial gauge could rest on a smooth surface. For each increment of load, the lateral and longitudinal deformations were noted. The lateral deformation was noted up to 1/3rd of the ultimate load for calculating Poisson's ratio. The bricks were loaded up to failure.

3.2 Tests on Mortar

Strength of masonry also depends on mix of mortar. The properties of masonry are evaluated using EN 1052:1-4 [29, 17-19]. IS 4326 recommends minimum 1:6 mix proportion of cement and sand [30]. In practice, in India, most of the masonry construction uses lower mix proportion of cement and sand. In this study, three mortar mixes were considered. Water to be added in each mix proportion was not mentioned in standard codes. As per IS: 2250 [31], "quantity of water to be added to mortar shall be such that working consistency is obtained, excess water shall be avoided". An optimum water content which gives maximum strength is found by trial and error. 7 days CS was determined. The result shows that mix 1:4, with w/c 0.60 gives maximum average CS. For mix 1:6 and 1:8, w/c was found to be 0.80. The water content which gives maximum strength in each proportion was noted, and the specimens were cast and tested for 28 days CS. MOE of mortar was determined using stress-strain values under axial compression test of individual mortar specimens. Cylinders of 100 x 200mm were used to find out MOE and PR of mortar. Mortar of mix 1:4, 1:6 and 1:8 were cast. Water added was according to the optimum water content. Mortar specimens kept in vertical position were subjected to axial compression. Load was applied gradually in equal increments. Three deflection DG with LC 0.002mm measured deformations, with maximum deformation of 12 mm. DG measured longitudinal and lateral deformation. The specimens were loaded up to 1/4th of ultimate compressive load.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Tests on Brick Units

WCBs (4.64 and 6.18) have relatively higher CS than CBB (2.19MPa). CS of CBB is less than the minimum permissible CS (3.5MPa), hence cannot be used in load bearing wall. Weights of bricks after 24 hours immersion in water and percentage of WA were calculated. Average WA for WCBs and CBB were 18.4, 19.7 and 17.4% respectively. Graph was plotted between normal stress and linear strain of the brick. MOE of individual bricks was obtained from the slope of the graph. Average value of MOE of WCB1 was obtained as 0.1667 GPa, WCB2 as 0.133 GPa and CBB as 0.0667 GPa. Lateral strain was evaluated from the lateral deformations measured along the side faces of the brick unit. A graph plotted between lateral and longitudinal strain and the average value of slope of the graph gave the PR of brick specimens. PR of WC1, WC2 and CBB was 0.217, 0.211 and 0.084 respectively.

4.2 Test results on masonry

Mortar was tested in compression at 28 days for ultimate load. CS for mixes 1:4, 1:6 and 1:8 were 10.1, 6.7 and 2.35N/mm^2. Cylinder specimens were used to find out the modulus of elasticity of mortar of different mix proportions. The linear axial deformation of mortar was observed from the vertical dial gauge. Slope of graph plotted between axial stress and strain for each mortar specimen gave MOE. Average MOE for mixes 1:4, 1:6 and 1:8 were 2.65, 2.0 and 1.167 GPa respectively. Lateral strain was evaluated from lateral deformations measured from curved surface of cylinder. Average slope of graph plotted between lateral and longitudinal strain gave PR of mortar. PR for mixes 1:4, 1:6 and 1:8 was 0.165, 0.117, and 0.119 respectively.

4.3 Comparison of Test results

The properties of the bricks are compared with values reported in literature or Codes in Table 1. The CS of the bricks was very low even for the WCBs compared to the values for Western countries [7]. Generally the strength is greater than 3.5 N/mm^2 which is the minimum requirement for strength of bricks for use in earthquake prone areas as per IS 4326 [30] and IS 13828 [32]. WA does not exceed 20% as specified by IS 1077 for bricks up to class 12.5. The average value of MOE of WCB1, WCB2 and CBB was obtained as 0.1667, 0.133 and 0.0667 GPa respectively. Bricks in Western countries have MOE between 3.5 and 34.0 GPa [7] [8]. Australian bricks have MOE from 7000 to 12000 MPa [9]. MOE of Indian bricks are very low compared to the results reported for Western countries, Australia and Shariq et al [26]. PR of WCB1, WCB2 and CBB was obtained as 0.217, 0.211 and 0.084 respectively. PR of the CBB is very low compared to the corresponding value for WCB1 and WCB2. PR of CBB is also very low compared to the values reported by Hendry [7], Lenczner [8], Dhanasekar [9] and Shariq et al [33] whereas the value of PR of WCB is comparable. The density of bricks decreases in the order solid block, Laterite block, WCB, concrete hollow block, CBB and interlocking blocks. It is to be noted that lighter bricks are preferred in seismic zones [34].

Table 2 compares the compressive strength for different mortars. The strengths correspond to the strengths for mixes reported in Varghese [35]. However they do not correspond to those specified in ASTM C270 [36]. As per EC8, for masonry in EQ zones, minimum mortar strength of 5 N/mm^2 is required which is satisfied by 1:4 and 1:6 mortars [37].

Table 1: Comparison of properties of bricks

Property	Kollam sample	Range of value
Compressive strength (MPa)	WC 4.64 6.18 CBB 2.19	Indian bricks 3-20 MPa Western countries 15-150 MPa
Water absorption (%)	WC 18.4 19.7 CB 17.4	Shall not be more than 20% as per IS 1077 [38]
Modulus of Elasticity	WC 0.1667GPa 0.133GPa CB 0.0667GPa	3.5GPa - 34.0 GPa
Poisson's ratio	WC 0.213 0.211 CB 0.084	Australian bricks : 0.12 – 0.29 [9] 0.13 Shariq et al [33] Schneider and Dickey [39]: Ungrouted clay masonry 0.23 and Grouted clay masonry 0.4
Density (kg/m^3)	WC 1612.31 1707.07 CB 1576.5	Lighter bricks are preferred in seismic zones

Table 2: Comparison of Cube Compressive Strength of Mortar of different mix proportions

Mix	28 Days compressive strength (N/mm^2)	Varghese [35] (N/mm^2)	Comparison with ASTM C270 [36]
1:4	10.1	7.5	The strengths are lower than that of M (17.2 MPa) and S (12.4 MPa) but comparable to N (5.2 MPa) mortars. M and S are for seismic zones whereas N is for general use.
1:6	6.7	3.0	
1:8	2.35	0.7	

The average value of modulus of elasticity obtained was 2.65 GPa for 1:4 mixes, 2.0 GPa for 1:6 mixes and 1.167 GPa for 1:8 mixes (Table 4). The elastic modulus of cement mortar (1:6) adopted commonly for brick masonry all over India is 10 to 15 times higher than that of the bricks. The values of elasticity modulus of mortar obtained experimentally are compared with results obtained elsewhere in Table 4. Poisson's ratio value of 0.165 was obtained for 1:4 mix, 0.117 for 1:6 mix, and 0.119 for 1:8 mix. Table 3 compares the value of Poisson's ratio of mortar obtained experimentally with other works reported in Literature. The value of Poisson's ratio experimentally determined agrees with that of Haach et al [40]. Poisson ratio is higher for richer mortars.

Table 3: Comparison of Poisson's Ratio of Mortar

Author	Mix proportion	Poisson's Ratio
Current work (Kollam sample)	1:4 1:6 1:8	0.165 0.117 0.119
Haach et al [40]	1:3 (w/c=0.8) 1:3 (w/c=0.9) 1:3 (w/c=1.0)	0.21 (cov=10%) 0.18 (cov=17%) 0.26 (4%)

Table 4: Comparison of densities of mortar

Property	Kollam sample	Range of value
Modulus of Elasticity	1:4 = 2.65 GPa 1:6 = 2.0 GPa 1:8 = 1.167 GPa	Varies between 9.6 and 23.4 GPa for various standard mixes [41]
Density	1:4 = 2132 1:6 = 2049.1 1:8 = 2022.3	1:3 (w/c = 0.8) 0.21 cov =10% 1:3 (w/c = 0.9) 0.18 cov=17% 1:3 (w/c=1.00) 0.26 cov= 4%

V. CONCLUSIONS

CS of CBB were found to be very less than that of WCB and also the CS of brick was less than the permissible compressive stress. WA of bricks was on the higher side even though within the limits prescribed by Indian standards. The mechanical properties of mortar reduce with lower mix proportions of mortar. The properties can be used to determine the characteristic CS of masonry using the EC6 expressions. The choice of parameters for the non-linear analysis is summarized below. It could be seen that WCB1 and CBB has better material properties than other types of masonry units. CBB showed lesser values of material properties compared to WCBs. Though both WCB and CBB satisfy requirement of strength of bricks for seismic zone, the WCB1 was chosen for the non – linear analysis. Mortars 1:4 and 1:6 have been recommended for seismic zones whereas mortar 1:8 is not recommended. Although mortars (1:4, 1:6, 1:8) satisfy strength requirements, they do not satisfy requirements of M and S mortars (for seismic zones) whereas they satisfy N mortars recommended for general use in ASTM C270. However for the non – linear analysis all three were chosen. So WCB-1 and combination of different mortar mixes were used for the numerical investigation of masonry walls. Suitable values of the variables chosen for the non linear dynamic analysis of the walls using FEM are given in Table 5.

Table 5: Properties of Different Materials Used for Analysis

Description	MOE (GPa)	PR	Density (kg/m^3)
WCB1	0.167	0.213	2.67
1:4 mix	2.65	0.165	0.444
1:6 mix	2	0.117	23.12
1:8 mix	1.167	0.119	0.251

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