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Effect of Precompression and Mortar Ratios on the In-Plane Shear Strength of Unreinforced Brick Masonry

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Abstract: This paper aims to study the In-plane shear strength of unreinforced brick masonry. Under lateral loads i.e. earthquake, wind, floods etc., it is commonly the walls that tend to undergo shear failure in most of the cases. The failure corresponding to these lateral loads during earthquake can be purely shear if the mortar is weak. Mortar is playing an important role in resisting lateral loads by inducing friction in presence of vertical precompression. Due to the importance of mortar, various mortar ratios are tested to find the effect of mortar ratios on the shear resisting properties of unreinforced brick masonry. Similarly, the frictional component of shear strength depends on vertical stresses, therefore, four different precompression levels are also selected and used. Standard brick unit prevalent in Pakistan is considered, similar to units that can be found also in neighboring countries like India, Iran and Bangladesh amongst others. The results showed that by using rich mortar helps in increasing the shear strength as compared to lean mortar. Four different mortar ratios are used which are common in construction of masonry structures. 12 samples each of 4 mortar ratios are tested. The shear strength parameters i.e. cohesion and coefficient of friction are monitored and observed and are related to the compressive strength of mortar as well as the mortar ratio. Empirical correlations are developed, which can be used for shear design of unreinforced masonry.

Keywords: *Shear, Shear Strength, Compression, Mortar, Unreinforced Brick Masonry.*

1 Introduction:

For centuries, masonry has been used as the most common material for the construction of load bearing and non-loading bearing walls, retaining walls, bridges etc. In the later years, however, steel and concrete has replaced it to some extent but it is still used for the construction of residential, educational and commercial constructions. (Hendry, 2001). Thus masonry is rendered to be of great importance and its response needs to be studied under various loading conditions. Masonry is a composite material consisting of units and a binding material to hold the units together. The units can be bricks, stones or concrete masonry units (CMUs). The binding material can be mortar of various ratios and composition. It has a much better response in heat insulation, acoustics and vertical compressive loading. However, despite of these advantages, masonry is weak in resisting in-plane lateral loads i.e. earthquake and wind loads. (Zhuge et al 1998). The failure of masonry varies depending on the loads, it is subjected too.

The capacity of a wall in shear comes from high moment of inertia around an axis, good quality work ensuring good compressive strength and tensile strength to some extent, which increases with the increase in load from upper stories. In a brick work building subjected to seismic loads, flat seismic inertial strengths grow in the walls and the floor and roof slabs. The floor and top slabs are called diaphragms where they exchange lateral loads to the horizontal load resisting system. These inertial strengths are relative to the mass of these structural parts and the speeding up at their level. The lateral load resistance of brick work structures is essentially because of in-plane shear safety of the masonry components. Accordingly, detailed examination on the in-plane shear behavior of brick work component subsequently gets to be necessary. (Christy 2012).

Brick Masonry comprises of masonry units connected together through mortar, thus masonry can be classified as a composite material. Being composite material, the response of masonry is unpredictable. The in-plane behavior cannot be predicted precisely because of complicated brick-mortar behavior. Notwithstanding advanced failure speculations for foreseeing failure modes for given conditions of stresses, models are present which can help anticipate the out of plane lateral strength of URBM piers by taking into consideration the vertically applied compressive loads.

This paper hence presents an experimental investigation on solid clay fired-brick masonry material for mechanical characterization. The experimental work included tests on triplets: for the estimation of bond strength in shear: cohesion parameter (c) and friction coefficient (μ) of Mohr-Coulomb model, besides tests on constituent materials i.e. brick units: for unit compression strength, water absorption and initial rate of absorption and mortar: for compression strength (fm).

Figure 1: Shear damages observed in load bearing walls of unreinforced masonry buildings and masonry infill of concrete buildings due to earthquake induced lateral loads.

(A): Diagonal shear cracks in masonry building walls observed during Wenchuan Earthquake. A building with six stories. Adopted from Feng Yuan et al. (2014).

The testing is performed using the standard testing procedures: EN 1052-3 (2002) for triplet tests, ASTM C-67-06 (2006) for masonry unit tests and ASTM C109/C109M-08 (2008) for mortar compression tests. Four types of mortar ratios are considered; 1: 4, 1: 5, 1: 6 and 1: 8. The leaner mortars are to be checked to give more economical mortars for masonry construction. It is essential to understand their impact on the mechanical properties of masonry. Empirical relationships are developed to relate the basic mechanical properties of masonry with mortar strength, mortar constituents and mix ratio. Also, an attempt is made to correlate the mechanical parameters with each other. These relationships can provide a useful means for future applications in the design and verification studies of masonry construction.

2 Experimental Exploration of Clay Fired Brick Masonry:

2.1 Experimental Tests Program:

The experimental testing for mechanical characterization of masonry comprised of tests on masonry units, mortar and masonry triplets. The testing is performed at the Material Testing Laboratory of Civil Engineering Department of UET Peshawar, Pakistan. The following sections briefly elaborate each of the tests.

2.2 Tests on Masonry Constituents Material:

2.2.1 Masonry Unit Tests Per ASTM C-67-06:

The present study has focused on exploring masonry of solid clay fired brick masonry units, common in various parts of Pakistan, which can also be found in other South Asian countries like India, Iran, Bangladesh, among others. The tests on brick units included water absorption test (on ten samples), initial rate of absorption (IRA) test (on 10 samples), compressive strength test (on 10 samples). The results of the experiments showed unit water absorption of 14.02% (COV 30.37%); IRA of 142.82 gm/min/30inch^2 (COV 25.19%); compressive strength of 9.729 MPa (COV 23.61%). The water absorption capacity which is less than 30% indicates fair quality of the unit. The IRA of unit which is greater than 30gm/min/30inch^2 indicates that it must be wetted enough before employing in the construction of masonry works.

2.2.2 Mortar Tests Per ASTM C109/C109M-08

Various types of mortars investigated in the present study included Cement-Sand mortars of different ratios. The different proportion in which the cement sand is mixed gives more workable and economical mortar for brick masonry construction (Naeem et al., 1996). The mortar ratios utilized are 1:4, 1:5, 1:6 and 1:8. Gradation test is performed on sand, see Figure 2 which revealed a well graded aggregate with fineness modulus of 2.73.

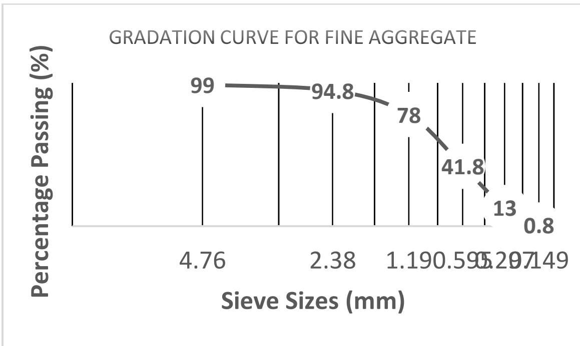

Figure 2 Fineness Modulus of Sand

Mortar cubes of size 50mmx50mm (ASTM C109) were prepared for the formerly discussed mortar types and tested after 28 days for compressive strength. A total of 24 mortar cubes (six samples for each mix proportion) were tested. Figure 3 shows the mean estimated compressive strength of each mortar cubes.

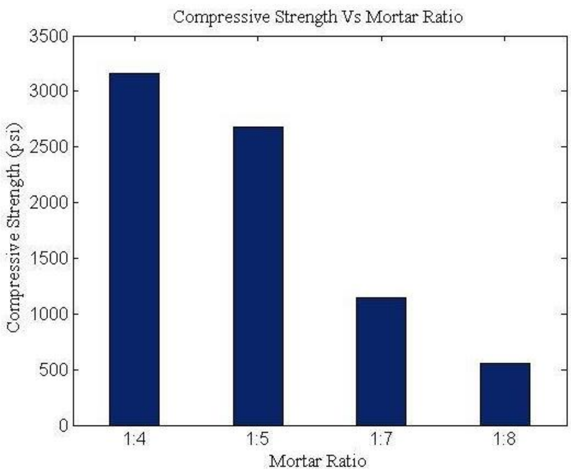

Figure 3 Mean Compressive Strength of Mortar Ratios, 28-days

It was observed that the Compressive Strength decreases as the mortar becomes leaner. On an average the strength reduction is in the range of 40 percent as the Mortar ratio changes from 1:4 to 1:8.

2.3 Tests on Masonry Assemblages

2.3.1 Masonry Triplets Tests Per EN-1052-3

The Triplet Tests were performed on masonry assemblages composed of three bricks using the EN-1052-3 testing setup (Figure 4).

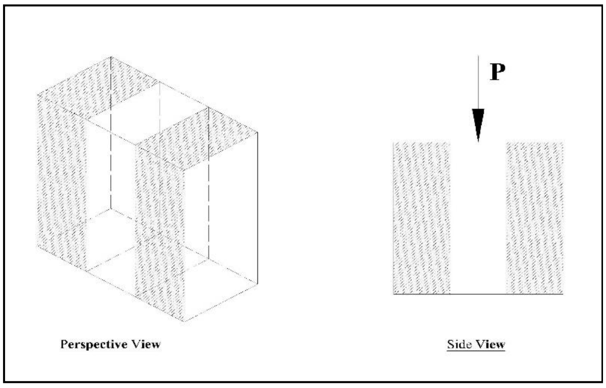

Figure 4 Triplet Test Specimen and Loading Setup

Assembly shown in Figure 5, represents the testing arrangement made to carry out the Triplet testing in accordance with EN1052-3. Four cases for pre-compression (0kg, 275kg, 643kg and 1010kg) were considered.

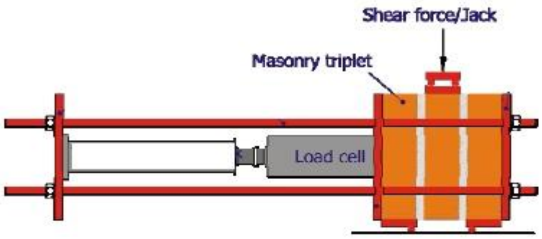

Figure 5 Triplet Test Assembly

Triplet test gives us a relation between Shear and Vertical Stress, which can be plotted to obtain the Mohr-Coulomb Envelope for the Shear Strength of Masonry.

$$\tau = c + \mu\sigma \qquad (1)$$

where τ is the in-plane shear strength, c corresponds to Cohesion i.e. the shear strength at zero pre-compression; μ is the coefficient of friction; σ shows the pre-compressive vertical stress on the prism. A total of 48 prism samples (3 samples prepared for each mortar ratio) tested under four different precompression levels.

Figure 6 represents the average shear strength for the various mortar ratios, it was observed that as the mortar ratio changes from 1: 8 to 1:6, 1:6 to 1:5 and 1:5 to 1:4, the shear strength on an average increases by 21 percent, 42 percent and 14 percent respectively. Similarly, the coefficient of friction is observed to vary as the mortar ratio changes. The variation is also shown in Figure 7.

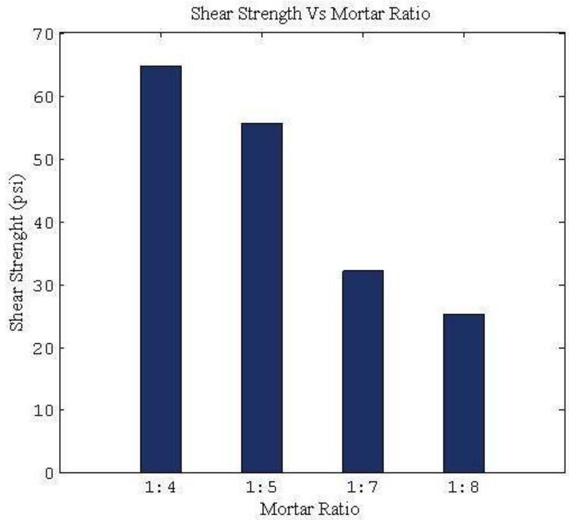

Figure 6 Shear Strength with respect to Mortar Ratio

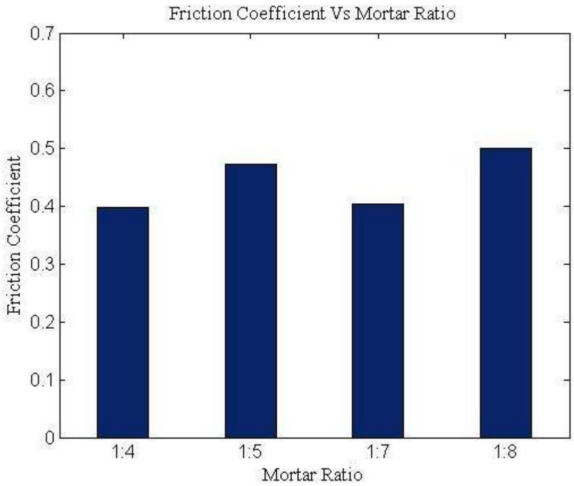

Figure 7 Coefficient of Friction with respect to Mortar Ratio

3 Simplified Empirical Relationships for Masonry Mechanical Properties:

The bond shear strength obtained experimentally for each mortar is related with the mortar compressive strength to develop simplified relationship for future use given either of the information on the compressive strength of mortar. Moreover, correlation is developed between the mechanical properties (bond shear strength and coefficient of friction) and mortar types and mix proportion.

3.1 Mortar Strength to Masonry Mechanical Properties

3.1.1 Mortar Strength to Masonry Bond Strength

A relation is developed between the mean bond shear strength in absence of normal Stresses, and the compressive strength of mortar. Nonlinear regression analysis is carried out and empirical equations are developed through best fitting line. The correlation is as follows:

$$c = 0.06\, f_m^{\ 0.8389} \qquad (2)$$

Where f_m (psi) is the compressive strength of mortar, Moreover, constrained regression analysis is carried out whereby the power of f_m is kept 0.80 and 1.0, in order to possibly further simplify the above equation.

$$c = 0.08\, f_m^{\ 0.80} \qquad (3)$$

$$c = 0.02\, f_m \qquad (4)$$

Either of the above equation may be utilized, for most of the practical cases, to get the masonry bond shear strength from the mortar compressive strength. Figure 8 shows the experimentally obtained data employed for correlating the bond strength to mortar strength and possible best fitting through regression (unconstrained and constrained) analysis.

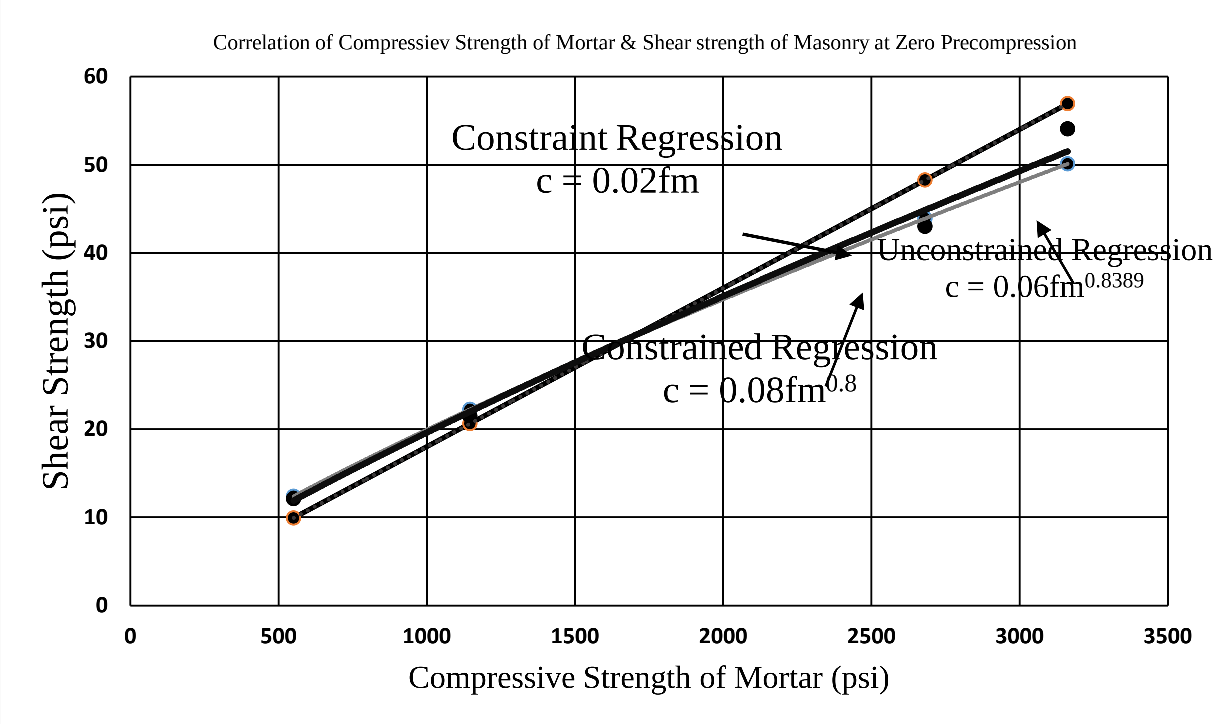

Figure 8 Relation between Masonry Bond Strength and Compressive Strength of Mortar

3.2 Mortar Mix Proportion to Masonry Mechanical Properties

3.2.1 Mortar Mix Proportion to Masonry Bond Strength and Friction Coefficient

The shear strength is obtained by plotting Normal precompression stresses against the shear stresses. The equations obtained are as follows.

<u>*Shear Strength:*</u>

$\tau = 64 + 0.39\sigma$, 1:4 – Mortar (5)

$\tau = 55 + 0.47\sigma$, 1:5 – Mortar (6)

$\tau = 32 - 0.40\sigma$, 1:6 – Mortar (7)

$\tau = 25 + 0.50\sigma$, 1:8 – Mortar (8)

The above equations represent the respective shear strengths for the different mortar ratios. The cohesion and coefficient of friction can be observed in the equation as it's in the same format as the Mohr-Coulomb equation.

4 Conclusions:

The paper gives the mechanical interpretation of solid fired clay brick masonry through experimental exploration. Laboratory tests were carried out on 24 mortar cubes and 48 masonry triplets for triplet tests. The effects of various mortar mix proportion and vertical stresses on the Shear strength are investigated.

Empirical correlations are developed between mortar compressive strength, mortar mix ratio and coefficient of friction. These correlations are first of their kind and are of great importance for practical use in masonry industry. The research can be utilized not only in Pakistan but also in the neighboring South Asian countries as the masonry properties doesn't vary substantially. The following conclusions are inferred based on the experimental study.

- If the mortar compression strength is known, the bond strength of masonry can be predicted as follow:
  Bond Strength (Cohesion) = 0.0597×Mortar Strength$^{0.8389}$

- Masonry bond strength and compressive strength increases as the mortar becomes richer.
- Masonry friction coefficient increases with increasing the relatively proportion of sand constituent in mortar.
- Cohesion component of Shear strength is increased as the mortar becomes richer or if the cement content is high.
- The Vertical precompression stress affects the Shear strength in a way that as the mortar becomes leaner or the sand content increases, the coefficient of friction increases but the effect of Coefficient of friction is dependent on the vertical precompression stress. So higher the precompression stress more is the contribution of friction in the shear strength of masonry.

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