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Experimental characterization of brick masonry for lateral strength evaluation

I. Khan, M. Ashraf, M. Fahim*
University of Engineering and Technology, Peshawar, Pakistan
**E-mail: drmfahim@uetpeshawar.edu.pk*

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Abstract. Brick masonry in solid clay units and cement-sand mortar is practised in many seismically active regions of Pakistan and also in other South Asian countries like India, Bangladesh, and others. The strength and behavior of brick masonry buildings are predominantly governed by the in-plane response of walls. The mechanical properties of masonry are essential input for the numerical models employed to estimate the in-plane response of brick masonry walls. This paper presents the mechanical properties of masonry constituent materials (brick and mortar) and brick masonry wallets for mechanical characterization. Masonry prisms (9 specimens) in three different mortar mix are tested for compression strength. A new test setup is developed and employed as part of this research study to conduct diagonal tension tests on masonry wallets (12 specimens) in a more stable and convenient position. Empirical relationships are also developed using regression analysis whereby the compressive strength of mortar is related to the compressive strength and diagonal tension strength of brick masonry. The mechanical characterization and the empirical relations will help in future applications in the context of design and assessment studies of brick masonry buildings.

1. Introduction

Brick masonry is one of the most widely used construction technique throughout the world, especially in the underdeveloped and developing countries. Brick masonry in solid clay units and cement-sand mortar is practiced throughout Pakistan and also in other South Asian countries like India, Bangladesh, and others. Unreinforced masonry (URM) has experienced major damages and collapses in the past earthquakes causing significant casualties and property loss [1–4]. After Kashmir earthquake of 2005, brick masonry has been extensively investigated experimentally at the Civil Engineering Department, University of Engineering and Technology, Peshawar, Pakistan [5–8]. However, there is a dire need for the development of analytical and numerical tools for the analysis and design of brick masonry structures. Mechanical characterization is an essential first step towards the development of more reliable numerical tools.

The behavior of unreinforced masonry material under lateral loads is dramatically different than steel and concrete due to its composite nature. The factors affecting the performance and behavior of unreinforced masonry structure are geometry, vertical stress and properties of constituent's material [5, 9, 10]. The mechanical properties of unreinforced masonry as a composite material are functions primarily of the mechanical properties of the individual masonry units, mortars, and the bond characteristics between units and mortar. Since the simplified hypotheses employed for concrete and steel cannot be utilized for brick masonry, the mechanical characterization of masonry can be performed through experimental investigations.

In brick masonry, when the connections at orthogonal walls and at floor-to-wall is properly achieved, the lateral loads are primarily resisted by in-plane response of walls [11, 12]. Many analytical models are available to estimate the in-plane response of brick masonry walls [12–16]. The mechanical properties of masonry are essential input for all these models. This paper presents mechanical properties of masonry constituent materials (brick and mortar) and brick masonry wallets for mechanical characterization. The

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paper also discusses the development of empirical relationships using regression analysis whereby the compressive strength of mortar is related with the compressive strength and diagonal tension strength of brick masonry. The mechanical characterization and the empirical relations will help in future applications in the context of design and assessment studies of brick masonry buildings.

2. Methods

The mechanical properties of masonry constituent materials were determined first, followed by compression and diagonal compression tests of masonry prims. Four types of tests were conducted on masonry units i.e. compressive strength of full unit, compressive strength of half unit, water absorption, and flexural tensile strength. The tests were performed following procedures specified in American Society of Testing and Materials (ASTM C-67). The most common ratio of cement sand mortar ranges from 1:4 to 1:8 in the prevailing masonry construction in Pakistan. Therefore, three different mortars with ratios 1:4, 1:6, and 1:8 were tested in compression according to ASTM C109.

Compression tests were conducted on masonry prisms of size 16 in. × 19 in. × 9 in. according to ASTM C 1314-03b as shown in Fig. 1. A total number of 9 prims were fabricated in running bond. However, one prism prepared in 1:8 mortar was damaged during handling.

Figure 1. Test setup for compressive strength of masonry prisms.

Tests were performed on masonry panels of size 48 in. × 48 in × 9 in. for the estimation of diagonal tension strength according to ASTM E519-02. The general practice is to fix the panel diagonally in two vertical jaws and the load is applied in vertical direction. However, as part of this research study, a new test setup was developed where the specimen are placed in a more stable horizontal position and the load is applied along the diagonal in an inclined direction as shown in Fig. 2.

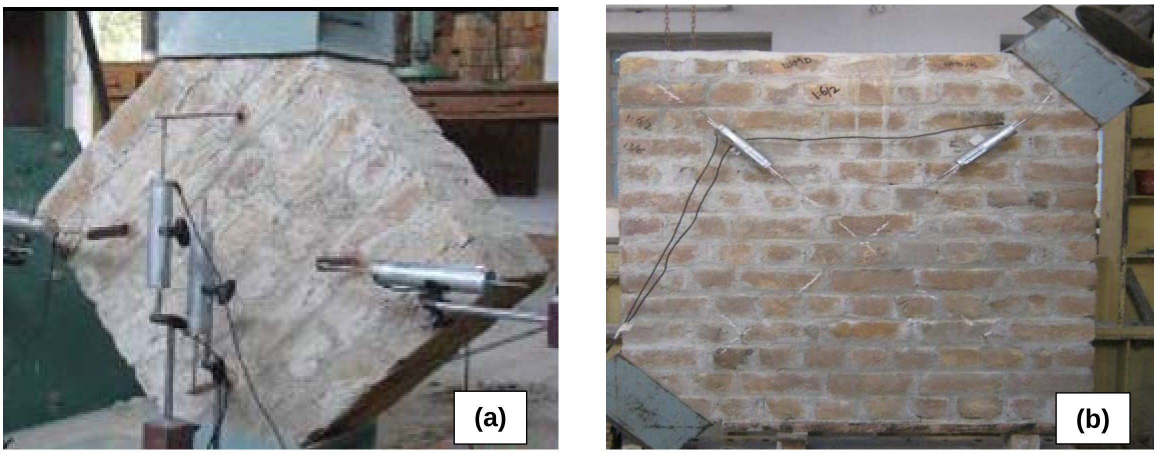

Figure 2. Test setup (a) previously used (b) newly developed.

3. Results and Discussion

3.1. Compressive Strength of Full Units

The results of compressive strength of full brick units are given in Table 1. The average value obtained for compressive strength is found to be 3194 psi and the coefficient of variation is found to be 16 %.

Table 1. Compressive strength of masonry units.

Sample No.	Length (in)	Width (in)	Area (in2)	Maximum Load (Tons)	Strength (psi)	Mean (psi)	COV (%)
1	9.00	4.25	38.25	25.8	1487	3194	15.88
2	8.75	4.12	36.09	41.7	2546		
3	8.75	4.12	36.09	63.3	3865		
4	8.62	4.06	35.04	63.5	3994		
5	8.50	4.06	34.53	62.9	4015		
6	8.75	4.00	35.00	35.4	2229		
7	8.75	4.12	36.09	53.4	3261		
8	8.62	4.06	35.04	66.1	4158		

The average compressive strength of masonry units found in various research studies conducted at University of Engineering and Technology, Peshawar is given in Table 2.

Table 2. Compressive strength of masonry units obtained during local research work.

S.No.	Title of Research Topic	Mean Compressive Strength of Unit (psi)	COV (%)
1	To Study the Modulus of Rigidity of Local Brick Masonry System [17]	2452	22.89
2	Seismic Risk Assessment of Unreinforced Brick Masonry Building System of Northern Pakistan [7]	3200	23.4
3	Performance Behavior of Confined Brick Masonry Building Under Seismic Demand [18]	2338	25
4	Seismic Risk Assessment of Buildings in Pakistan (Case Study Abbottabad City) [19]	1803	26.7
5	Development of low cost and efficient Retrofitting Technique for Unreinforced Masonry Buildings [6]	3170	13.8
6	This study	3194	15.88
	Overall Mean compressive strength	2692	21.28

The results obtained by various researchers reveal a significant variation in the compressive strength of masonry units available in the local market. The main reasons are the difference in properties of the raw material used and burning temperature during manufacturing. According to guidelines of Earthquake Rehabilitation and Reconstruction Authority (ERRA) Pakistan, the mean compressive strength of masonry unit should comply with the minimum value of 1000 psi or 6.89 MPa, whereas according to Eurocode-8, the minimum acceptable normalized compressive strength of a masonry unit, normal to the bed face, should be equal or greater than 725 Psi or 5.0 MPa. The results of the previous research work and this research show that the strength of local manufactured brick is quite satisfactory and in compliance with code requirements irrespective of variability in the mean strength.

3.2. Compressive Strength of Half Units

The ASTM standard recommends compressive strength tests to be performed on half unit, although many researchers use full units to find compressive strength of masonry units. Therefore, in this study both full and half bricks were used for finding compressive strength of bricks. The result of compressive strength of half scale brick units are given in Table 3. The mean strength was found to be 2216 psi and coefficient of variation is 28 %.

Table 3. Compressive strength of half masonry units.

Sample No.	Length (in)	Width (in)	Area (in^2)	Maximum Load (Tons)	Strength (psi)	Mean (psi)	COV (%)
1	4.3125	4.125	17.79	23.5	2912		
2	4.25	4.125	17.53	23.7	2980		
3	4.3125	4.1875	18.06	13.3	1623		
4	4.4375	4.25	18.86	10.8	1262	2216	27.96
5	4.1875	4.0625	17.01	15.6	2021		
6	4.25	4.125	17.53	21.9	2753		
7	4.375	4.25	18.59	17.7	2098		
8	4.1875	4.25	17.80	16.8	2081		

A comparison of the results obtained for full and half units reveal that the mean strength in the former case is 44 % more than the latter. However, in both cases the mean strength is well above the Building Code of Pakistan recommended minimum limit of 8.25 MPa (1200 psi) [20].

3.3. Water Absorption of Masonry Units

The results of water absorption of the brick specimens carried out according to ASTM C-67 are shown in Table 4. Water absorption is very important parameter which influence masonry and mortar bond significantly. A total of five specimens were tested for water absorption. The mean value for water absorption was found to be 21.36 % and coefficient of variation was found to be 10 %. Farhat [17], Naseer [18] and Shahzada [19] found water absorption for brick units as 19.3 %, 19.33 % and 23.00 % respectively.

Table 4. Water absorption of masonry units.

Sample No.	Dry Weight of Samples (Ibs)	Wet Weight of Samples (Ibs)	% Absorption	Mean	% CV
1	5.757	6.797	18.1		
2	5.761	6.956	20.7		
3	5.885	7.198	22.3	21.36	10 %
4	6.114	7.555	23.6		
5	6.422	7.842	22.1		

The absorption of brick greatly influence the tensile and shear bond strength of the masonry. The highly absorptive unit has lesser strength due to that fact that brick unit absorb water from mortar layer after laying and leaves small amount of water for cement hydration which results in weak mortar formation and consequently in the weakening of masonry. The recommended value of water absorption for first class brick is not more than 20 %. Hence mean value of water absorption of local manufactured brick is almost equal to the recommended value.

3.4. Flexural Tensile Strength of Masonry Units

The tests for flexural tensile strength of brick specimens was carried out according to section 6 of ASTM C-67. The results are shown in Table 5. The mean value for tensile strength was found to be 913 psi whereas the coefficient of variation was 34 %. Ashraf [6] and Shazada [19] obtained the values of flexural tensile strength of masonry units as 919 psi and 479 psi respectively.

Table 5. Flexural tensile strength of masonry units.

Sample No.	Size (in)	Ultimate Vertical Load (Ton)	Section Modulus (in^3)	M_{cent} (lb.in)	Flexure tensile strength (psi)	Mean (psi)	COV (%)
1	9×4.25×3	0.98	6.4	4320	678		
2	8.69×4.12×3.0	1.65	6.2	6989	1130		
3	8.88×4×2.75	1.56	5.0	6769	1343	913	34 %
4	9×4.25×3.0	1.16	6.4	5113	802		
5	9×4.25×3.0	0.89	6.4	3923	615		

3.5. Compressive Strength of Mortar

In order to obtain a workable mortar, water cement ratio was determined taking into account the moisture content of sand. Gradation curves for two sand samples are shown in Fig. 3 and 4. The fineness modulus of sand in all tests was found in the ASTM recommended range of 2.3 to 3.1. Hence the sand is well graded for mortar preparation.

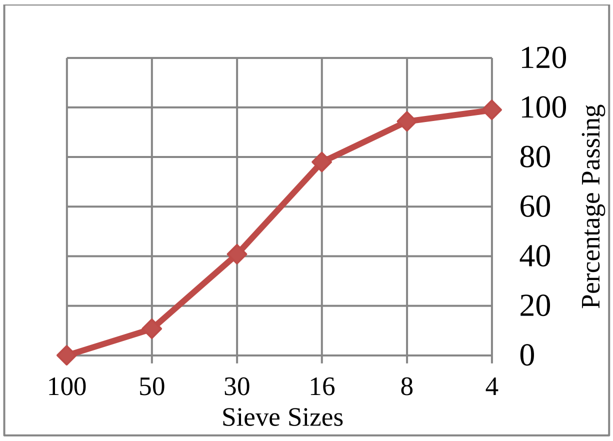

Figure 3. Gradation curve for sand sample 1.

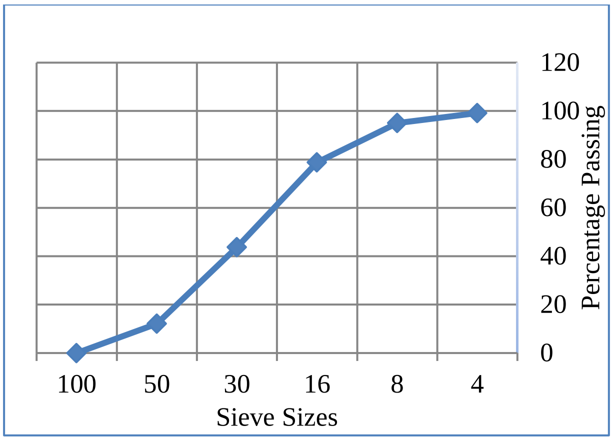

Figure 4. Gradation curve for sand sample 2.

Mortar cubes of size 2" x2"x2" were prepared with specified ratio of mortar using the determined water cement ratio. The average compressive strengths were found to be 1961 psi, 840 psi, and 311 psi as shown in Fig. 5. These results show a significant increase in mortar strength with the increase in cement content.

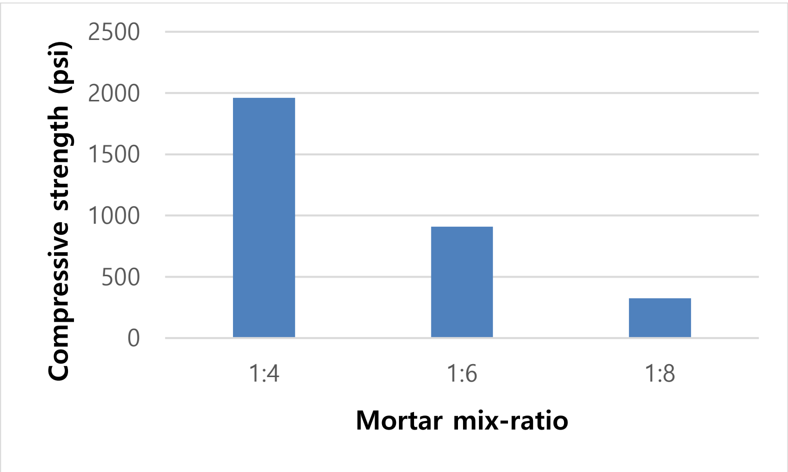

Figure 5. Mean compressive strength (28 days) of mortar cubes.

3.6. Compressive Strength of Masonry Prism

The average compressive strengths were found to be 518, 586 and 408 psi for 1:4, 1:6, and 1:8 mortars respectively as given in Table 6. Surprisingly, the compressive strength of prims in 1:6 mortar was more than the ones in 1:4 mortar.

Table 6. Compressive strength of masonry prisms.

Mortar mix Ratio	W/C Ratio	No	Area (in^2)	Maximum Load (Tons)	Strength (psi)	Mean (psi)	COV (%)
1:4	1	1	135.78	27.6	448	518	22 %
		2	137.38	28.5	457		
		3	135.11	39.8	649		
1:6	1.5	1	139.18	32.6	516	586	13 %
		2	136.82	35.5	572		
		3	137.53	41.8	670		
1:8	1.8	1	140.86	23.6	369	408	13 %
		2	138.74	28.1	446		

The compressive strength of masonry has also been investigated by various other researchers at UET Peshawar, Pakistan. The results are summarized in Table 7.

Table 7. Mean compressive strength of masonry obtained during local research work.

S. No.	Title of Research Topic	Mortar Type	Mortar Mix Ratio	Mean Compressive Strength (psi)
1	To Study the Modulus of Rigidity of Local Brick Masonry System [17]	Cement Sand (CS)	1:4	655
			1:6	575
			1:8	525
			1:10	395
		Cement Khaka (CK)	1:4	781
			1:6	719
			1:8	685
			1:10	532
		Cement Sand Khaka (CSK)	1:2:2	685
			1:3:3	648
			1:4:4	628
			1:5:5	516
2	Seismic Risk Assessment of Unreinforced Brick Masonry Building System of Northern Pakistan [7]	CSK	1:4:4	658
3	Performance Behavior of Confined Brick Masonry Building Under Seismic Demand [18]	CSK	1:4:4	839
4	Seismic Risk Assessment of Buildings in Pakistan (Case Study Abbottabad City) [19]	CS	1:6	438
5	Development of low cost and efficient Retrofitting Technique for Unreinforced Masonry Buildings [6]	CS	1:8	656

3.7. Diagonal Tension Tests of Masonry Prism

Diagonal tension test setup is used based on the assumption that pure shear is introduced in the specimen and the specimen cracks when the principal stress at the center of specimen reaches tensile strength of masonry. However, due to non-uniformity of stresses, the specimen is not under pure shear [21, 22]. Therefore, the analytical relation developed by Magenes et al. [22] is used to estimate the diagonal tensile strength of the specimens.

$$f_t = \frac{0.5P}{t(l_1 + l_2)} \tag{1}$$

where f_t denotes diagonal tensile strength, P is the maximum applied load, l_1 and l_2 are lengths of the two sides of the specimen, and t is the thickness of specimen. A total number of 12 specimens were tested for tensile strength estimation and the results are given in Table 8.

Table 8. Shear strength of masonry prisms.

Sample Size	Mortar mix Ratio	No	Shear Strength (psi)	Mean strength (psi)	COV (%)
48” × 48”	1:4	1	41.35	33.66	20
		2	31.28		
		3	28.35		
48” × 48”	1:6	1	20.71	26.16	38
		2	20.00		
		3	37.78		
48” × 48”	1:8	1	28.38	19.36	40
		2	14.84		
		3	14.85		
29” × 27”	1:6	1	30.40	32.46	11
		2	30.28		
		3	36.71		

The typical damage patterns during diagonal tension tests are shown in Fig. 6. The crack at failure follows bed and head joints of masonry. This implies that mortar and the bond strength between mortar and bricks contribute significantly to the masonry strength. Specimens in mortar mix 1:6 were tested in two different sizes, namely 48” × 48” and 29” × 27”. The mean shear strength was found to be 24 % higher in case of smaller specimens.

Figure 6. Typical damage pattern during diagonal tension tests.

4. *Empirical Relationships for Mechanical Properties of Masonry*

The mechanical properties of masonry (compressive and tensile strength) obtained experimentally are related to the compressive strength of mortar in order to develop simple empirical relationships for future applications.

4.1. Mortar Strength to Compressive Strength of Masonry

The mortar compressive strength is correlated with the masonry compressive strength using past data and results obtained in this study. The mean mortar compressive strength for a particular mix ratio is plotted against mean compressive strength of masonry as shown in Fig. 7. The past data of Shah [17], Shazada [19], and Ashraf [6] have been plotted. Linear regression analysis is used to develop an empirical relationship between mortar compressive strength and masonry compressive strength as:

$$f_{mc} = 0.0881 f_m + 451.91 \tag{2}$$

where f_{mc} is masonry compressive strength (psi) and f_m is mortar compressive strength (psi).

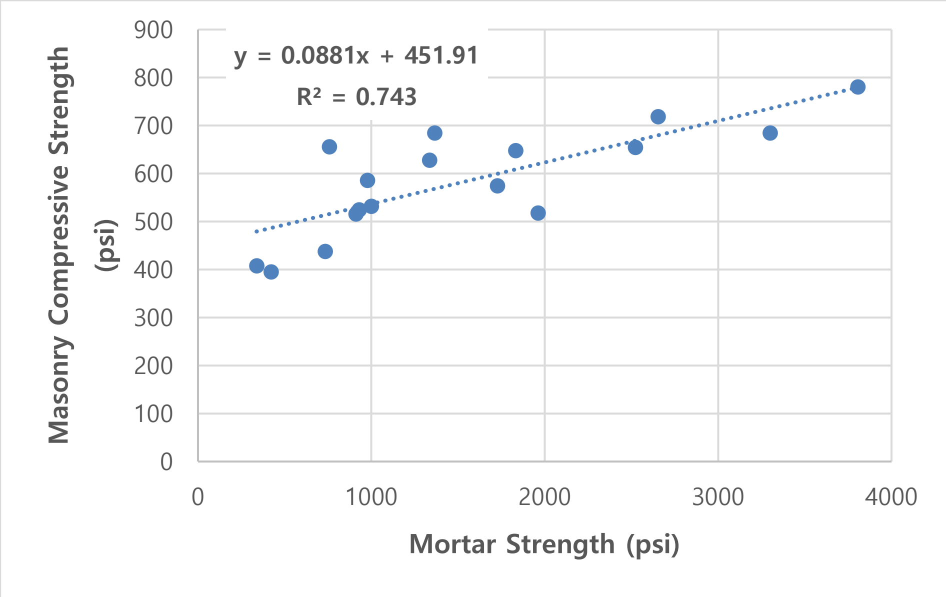

Figure 7. Relation between mortar strength and masonry compressive strength.

4.2. Mortar Strength to Masonry Tensile Strength

The mortar compressive strength is correlated with the masonry diagonal tension strength using past data [19] and results obtained in this study. The mean mortar compressive strength for a particular mix ratio is plotted against mean diagonal tension strength of masonry as shown in Fig. 8. Linear regression analysis is used to develop an empirical relationship between mortar compressive strength and masonry diagonal tension strength as:

$$f_t = 0.0085 f_m + 18.79 \quad (3)$$

where f_t is masonry diagonal tension strength (psi) and f_m is mortar compressive strength (psi).

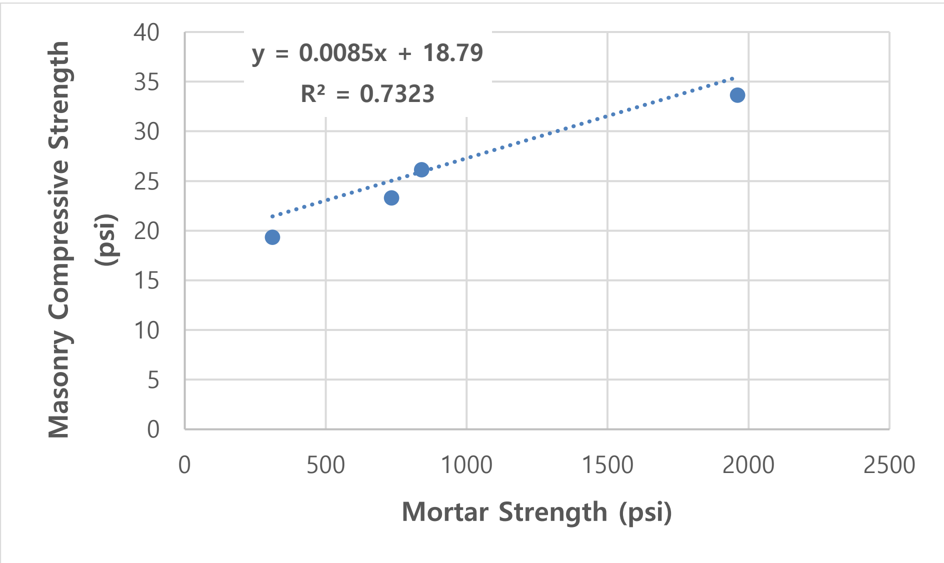

Figure 8. Relation between mortar strength and masonry tensile strength.

5. Conclusions

The following conclusions can be derived based on the results obtained in the experimental part of this study.

1. The mean compressive strength of masonry units (3706 psi for full units and 1928 psi for half units) is well above the minimum recommended values of national and international building codes. However, there is a large variation in the compressive strength of commonly used mortar (1961 psi for 1:4

mortar and 311 for 1:8 mortar). Therefore, the masonry strength is generally governed by the strength of mortar and the bond between mortar and masonry units.

2. The past practice for diagonal tension tests was to fix the masonry wallets diagonally in two vertical jaws and the load was applied in the vertical direction. However, as part of this research study, a new test setup was developed where the specimen are placed in a more stable horizontal position and the load is applied along the diagonal in an inclined direction. The new test setup was successfully used for diagonal tension tests of 12 specimens.

3. Masonry compressive strength and diagonal tension strength decreases with increase of sand proportion in mortar mix. The mean compressive strength is decreased by 21.24 % for specimens in 1:8 mortar as compared to specimens in 1:4 mortar. Similarly, the mean diagonal tension strength is decreased by 42.48 % for specimens in 1:8 mortar as compared to specimens in 1:4 mortar.

4. Two empirical relationships are developed correlated mortar compressive strength with masonry compressive strength and diagonal tension tests.

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Contacts:

Imtiaz Khan, engrimtiaz84@gmail.com

Mohammad Ashraf, mashraf@uetpeshawar.edu.pk

Muhammad Fahim, drmfahim@uetpeshawar.edu.pk