EXPERIMENTAL INVESTIGATION OF VARIOUS PROPERTIES OF BRICK MASONRY AT DIFFERENT GRADES OF MORTAR

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by

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DECLARATION

I, **MOHD AASIF RASOOL** (11507293), hereby declare that this submission is my own work and that to the best of my insight and conviction, it contains no material beforehand distributed or composed by other individual or office. No material which has been acknowledged for reward of some other degree or certificate of the college or other organization of higher learning with the exception of where due affirmations have been made in the content. It was arranged and displayed under the direction and supervision of **Ms. Mandeep Kaur** (Assistant Professor) and **Mr. Paramveer Singh** (Assistant Professor).

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CERTIFICATE

This is to certify that **MOHD AASIF RASOOL** under Registration No. **11507293** has prepared the dissertation report titled "**Experimental investigation of various properties of Brick Masonry at different grades of Mortar**" under my direction. This is a bonafide work of the above competitor and has been submitted to me in fractional satisfaction of the prerequisite for the honour of Masters of Technology in Civil Engineering.

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The fulfilment and elation that go with the effective finishing of any errand would be fragmented without specifying the people whose steady direction and support made it conceivable.

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I am profoundly obligated towards the other faculty members particularly who extended their assistance to me specifically or in a roundabout way and I am thankful to every one of them without whom it would have been unimaginable for me to finish my work in time.

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Signature of Student

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ABSTRACT

The present research aims at studying the behavior of masonry brick prisms with different grades of mortar and to estimate the percentage loss of strength in saturated samples. To relate the accuracy of present research findings, comparison has been made with past research works. Various control points on stress-strain curves were developed and verified using numerical models. Study reveals that masonry compressive strength is well dependent on mortar strength. It has been observed that despite less compressive strength of masonry prisms with low mortar grades, these exhibit a little ductile behavior than masonry prisms with rich mortar grades. The percentage compressive strength loss in masonry subjected to submerged conditions is estimated. The study also aims at experimentally evaluating shear strength of saturated and unsaturated brick masonry by different methods and to relate the experimental findings with numerical models. Masonry triplet test and diagonal compression test have been performed to get the shear strength, so this work can be helpful to relate the accuracy of triplet test and diagonal compression test. One of the most important material properties of the brick structure is shear strength which is inferred in light of both experimental and numerical methods as its correct definition assumes a vital part in the behavior of brick masonry under seismic actions. Study reveals that bond strength majorly influences shear strength of brick masonry. The percentage loss in shear strength when specimens are subjected to completely saturated conditions is estimated. So this exploration work can be very valuable to give some kind of constraining plan quality to houses subjected to floods where the strength under the standing water diminishes.

Keywords: *Brick masonry prisms, stress-strain curve, compressive strength, Shear strength, triplet and diagonal compression test, mortar grade*.

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LIST OF SYMBOLS

%	Percentage
MPa	Mega Pascal
mm	Millimetre
ºC	Degree Celsius
N	Newton
α_h	Seismic coefficient
sec	Second
f_b	Bond strength of mortar to brick
f_c	Mortar compressive strength
f_{tm}	Flexural tensile strength of mortar
f'_b	Compressive strength of brick unit
f'_j	Compressive strength of mortar
f'_m	Compressive strength of brick masonry
E_m	Modulus of Elasticity
f'_m	Ultimate masonry compressive strength
H	Hour

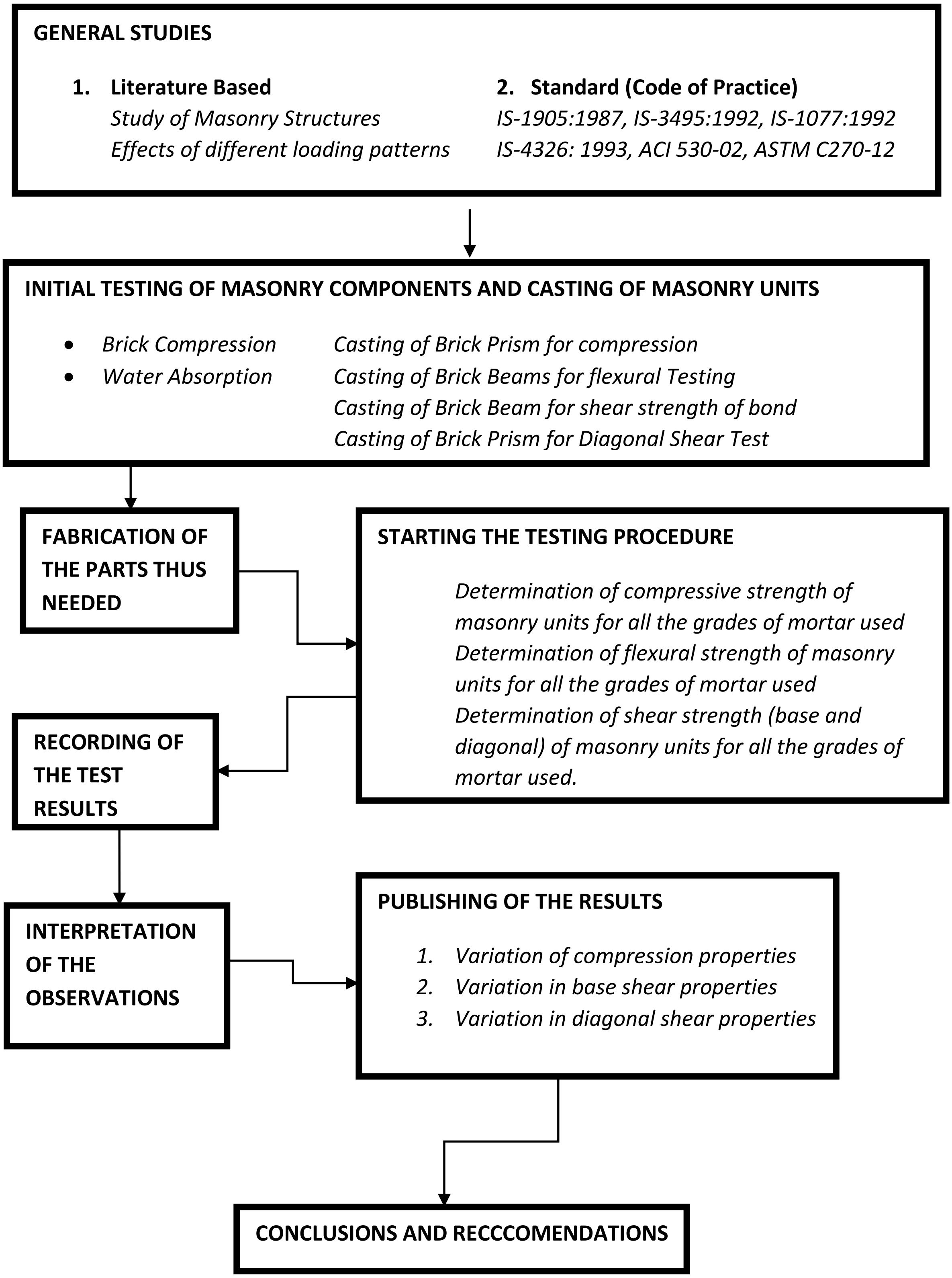
Chapter 1

Introduction

1.1 General Background

Brick masonry is a two-phase material comprising of bricks and mortar joints, orchestrated in an occasional manner. It is a non-homogeneous and anisotropic material and shows non-linear behaviour. As the cost of the material is low, it is utilized as a part of a wide range of structures far and wide. The stiffness and strength of masonry structure generally lies between the individual strengths of brick and mortar. Despite its good sound and heat insulation properties, it is weak in tension. Therefore, it is provided to resist compressive forces majorly. Compressive strength of masonry depends on the thickness of mortar bed joint. To experimentally evaluate the masonry compressive strength, tests suggested by bureau of Indian standards and ASTM are employed to get the same. As a reasonable other option to tedious lab tests, numerical and analytical techniques have pulled in broad consideration in research group and also in industry. The most comprehensive approach is to model each brick and each mortar joint in the masonry. This can be achieved by the application of finite element technique. FEM analysis can be applied to get the nature of stresses developed in the masonry assemblage. In order to carry out the analysis, mortar joint thickness, Poisson's ratio of both bricks and mortar are to be considered. Multilayer model, one-step homogenization approach, two-step homogenization method and asymptotic homogenization strategies can be utilized as a part of blend with FEM yet these request concentrated computational endeavours. Neither of them has taken into account the specific pattern of bricks and mortar nor have fully exploited the periodicity of geometry and other field quantities. A micro homogenization technique alleged "Eigen Strain Homogenization Method" can be executed to model brick work structures. Important material properties of the brick work structure will be inferred in light of strain energy approach.

1.2 Structure of the Project



Chapter 2

Terminology

Term	**Symbol**
Bond strength of mortar to brick	f_b
Mortar compressive strength	f_c
Flexural tensile strength of mortar	f_{tm}
Compressive strength of brick unit	f'_b
Compressive strength of mortar	f'_j
Compressive strength of brick masonry	f'_m
Modulus of Elasticity	E_m
Ultimate masonry compressive strength	f'_m

Chapter 3

Review of literature

3.1 General

Numerous seismic tremor reports expressed out the overwhelming harms done to brick masonry structures. Because of common earthquake tremors, the vast majority of the provincial houses were harmed in fragile fall because of absence of appropriate building design. The brick masonry is the minimum comprehended in the part of execution and quality related parameters because of its complex behaviour and non-homogeneity. In India fly ash generated each year is about 100 million tonnes. The government of India passed a law in October 2005 stating that for the manufacture of clay bricks used in construction activities, a minimum of 25 percent of fly ash should be used within a 50 km radius of coal burning thermal power plants. To understand the behavior of masonry structures in India, it is important to concentrate the past research and to recognize the research gap and the issue to be examined.

3.2 Brick

To understand the nature of stresses developed in the mortar joint and brick in the masonry, stress-strain behaviour of masonry were examined through prism tests, it was concluded that bricks develop lateral compression and mortar joints develop lateral tension [1]. Under compression, mortar deforms more in comparison with brick and leads to lateral expansion. [2]. Specimens consisting of richer mortar mixes show lesser deformations. It is also dependent on type of sand, mortar grade and joint thickness. [3]. Shape and size of frog affect the strength and bonding of brick masonry**.** Maximum strength was achieved for 5mm to 10mm size of mortar joint. [4]. Brick consists of small micro pores and its suction capacity depends on amount, size and shape of pores. [5]. There should be no moisture on the surface of brick at the time of laying [6]. In brick masonry, bricks adopted are stiffer and strong in comparison with mortar in western countries according to the literature available. Their compressive strength lies in between 15-150 MPa and modulus of elasticity lies in the range of 3500 and 34000 MPa [7, 8]. However, in India bricks show relatively lower strength (3–20 MPa) and low elastic modulus (300–15000 MPa) [9-12]. Compressive strength of bricks should be at least 3.5 MPa to perform well under loads and that the water absorption of bricks should be below 20% [13]. If lean mortar is adopted in masonry, there is abrupt failure in masonry due to weak bonding between bricks and mortar [14].

3.3 Mortar

The thickness of mortar material and brick material govern the strength of brick masonry in compression. More the thickness of brick material than mortar thickness, stronger the masonry [15]. Poor bond is sometimes a major weakness of brickwork. This strength of bond depends on both mortar as well as on masonry units. Bond strength can be improved by increasing the area of frog and using rich mortars [16]. The amount of lime present in mortar, at the mortar-unit interface generally acts as a weak layer. The cement mortar undergoes linear elastic deformation and remains as quasi-brittle material during masonry failure. The non-linear behaviour of masonry is majorly influenced by mortar [17]. The effective curing within the bricks can reduce the porosity and increase the mortar capacity [18].

3.4 Relationship between brick, mortar and masonry compressive strength

Masonry compressive strength is an important parameter for the analysis and design of masonry elements [19]. However, it is not always easy to practically determine the compressive strength and therefore many researchers [14, 15, 19] have proposed to develop an empirical relation for compressive strengths of brick unit, mortar and masonry as shown:

$$\mathbf{f'_m = K f'^{\alpha}_b \times f'^{\beta}_j} \qquad \textbf{(1)}$$

Where K, α and β are constants, and f'_b , f'_j and f'_m are the brick unit, mortar and masonry compressive strengths respectively. Eurocode gives a range of K values, while prescribing α and β as 0.7 and 0.3 respectively [20]. The values of K depend on the characteristics of bricks and the strength of bond joining bricks and mortar. The value of β is lower than α, which shows that the masonry compressive strength (f'_m) is more governed by brick unit compressive strength (f'_b) than mortar compressive strength (f'_j).

3.5 Relationship between masonry compressive strength and Modulus of Elasticity

The Modulus of Elasticity (E_m) of brick masonry is evaluated as the chord modulus of stress-strain curve for the linear part, which is generally taken between 5% to 33% of the peak masonry compressive strength (f'_m) on the rising limb [21]. The secant modulus at $0.25f'_m$ is also used to find the masonry Modulus of Elasticity [14]. Modulus of elasticity and ultimate compressive strength are related with each other as per following expression:

$$\boldsymbol{E_m = kf'_m} \tag{2}$$

Where k is a constant. FEMA 306 (1999) recommended E_m equal to $550f'_m$ for existing masonry and MSJC code (2002) recommended E_m equal to $700f'_m$ for modern masonry. The Canadian masonry code (CSA 2004) proposed a higher value of $E_m = 850f'_m$ for brick masonry. Euro code 6 (CEN 2005) recommends E_m in the range of $1000f'_m$. E_m Can be $750f'_m$ also [21]. In addition a wide range of variation is seen in modulus of elasticity and compressive strengths of newly constructed clay brick masonry in India i.e.; $E_m$ranges from $250f'_m$ to $1100f'_m$ [19]. It was also observed that E_m ranges from $210f'_m$ to $1670f'_m$.

3.6 Numerical masonry compression stress-strain model

Accurate non-linear masonry analysis is dependent on compression stress-strain behaviour. The deformation modes of masonry are dependent on its stress-strain behaviour [19]. The "modified" Kent-Park model can be useful for determination of stress-strain behaviour of masonry. In this model, a parabolic ascending stress-strain curve is followed by a linear descending part. At 20% of ultimate peak compressive strength, curve has a horizontal plateau [22].

The numerical stress-strain model matches with stress-strain curve obtained experimentally until the peak stress is reached according to following expression: [19]

$$\boldsymbol{\frac{f_m}{f'_m} = 2\frac{\varepsilon_m}{\varepsilon'_m} - \left(\frac{\varepsilon_m}{\varepsilon'_m}\right)^2} \tag{3}$$

Where f_m and ε_m represent masonry stress and strain respectively and ε'_m is masonry strain corresponding to f'_m. The immediate post-peak descending part was also represented using above relation. Equation 7 can be used to calculate masonry strain at peak strength (ε'_m), where a, b and c are constants having values of 0.27, 0.25 and 0.7 respectively.

$$\boldsymbol{\varepsilon'_m = \frac{af'_m}{{f'_j}^b {E_m}^c}} \tag{4}$$

3.7 ASSEMBLAGE MATERIAL PROPERTIES

3.7.1 Compressive Strength

The compressive strength of the masonry structure plays an important role in the structural design of masonry. The bureau of Indian standard gives some numeric values for basic compressive strength also [23]. In the present scenario advanced 3D models can be used to estimate compressive strength of masonry [24]. The compressive strength of prism depends on mortar strength to block strength ratio [25]. Due to presence of moisture, drop in compressive strength and stiffness is registered which is influenced by the size of pores [26]. According to MSJC Specifications the "Unit Strength Method" can be used to estimate the masonry compressive strength by considering each constituent material or "Prism Testing Method" is used by testing the properties of masonry assemblage as a whole [27].

3.7.1.1 Unit Strength Method

The material properties in the masonry must conform to ASTM standards. In this method properties of individual materials like bricks, grout, mortar are calculated. There have been various endeavours by scientists to relate the masonry compressive strength with compressive qualities of unit, mortar and grout. The determination of strength properties of constituents like brick, mortar based on this method are necessarily conservative. The correlations provided in MSJC Specifications represent a lower-bound to experimental results .

3.7.1.2 Prism Test Method

Prism testing of brick masonry is preferred over constituent material testing. Prism testing gives more accurate estimation of masonry compressive strength. It can be carried as per ASTM E 447 Test Methods for the computation of Masonry Prism Compressive Strength.

3.7.2 Shear Strength

The shear strength of the masonry structure is well dependent on individual characteristics of unit, mortar and grout. Shear failure is said to occur when mortar joints develop step-cracks or when splitting of units will occur. Increase in compressive strength of the unit can enhance the splitting strength of units. For masonry triplets presence of moisture is responsible for decrease in shear strength [28]. Unit splitting occurs in heavily axially loaded shear walls and in brick assemblages with rich mortar and weak units. Mortar joint cracking is a common shear failure of masonry. This failure is influenced by properties of both units and mortar.

Bond strength also influence shear failure of brick masonry. Shear strength can be determined experimentally by performing triplet tests on masonry in accordance with EN 1052-3 [29]. Triplet test is easy to perform and preferable but it is difficult to execute on existing masonry. To determine shear strength of new masonry wall and existing one, diagonal compression test can be performed in line with ASTM 509-2010 [30-32]. So this work can be helpful to relate the accuracy of triplet test and diagonal compression test. Therefore this study aims at finding the shear strength of masonry specimens and the percentage loss in shear strength when specimens are subjected to completely saturated conditions. As a reasonable other option to tedious lab tests, numerical and analytical techniques have pulled in broad consideration in research group and also in industry. Shear strength can be determined using pre-evaluated values proposed by Italian seismic code and Eurocode 6 [33]. Different numerical models are also available to interpret the experimental results [34].

3.7.2.1 Triplet test: The shear strength f_s is given by Eq. (5)

$$\boldsymbol{f_s = \frac{P_{max}}{2A_i}} \quad \textbf{(5)}$$

P_{max} is the ultimate load and A_i is area of specimen parallel to mortar joint.

3.7.2.2 Diagonal shear: The shear strength τ_0 can be obtained by means of Eq. (6)

$$\boldsymbol{\tau_0 = 0.707\frac{F_{ult}}{A_n}} \quad \textbf{(6)}$$

Where F_{ult} is the load at failure and A_n is the net area of the specimen, calculated as follows:

$$\boldsymbol{A_n = \frac{(w+h)t}{2}} \quad \textbf{(7)}$$

Where (w) is the specimen width, (h) is the specimen height, (t) is the thickness of the specimen

If shear strength is assumed equal to ultimate principal tensile stress, then it is given by Eq. (8)

$$\boldsymbol{\tau_0 = 0.5\frac{F_{ult}}{A_n}} \quad \textbf{(8)}$$

Shear strength [35] is also given by Eq. (9)

$$\boldsymbol{\tau_0 = 0.33\frac{F_{ult}}{A_n}} \quad \textbf{(9)}$$

3.7.3 Flexural Tensile Strength

Cracking of unreinforced brick masonry should be avoided as it may lead to failure. Therefore, the flexural tensile strength plays vital role in unreinforced masonry. It is the bond strength of masonry in flexure. It depends on direction of loading, type of mortar and units. Flexural tensile strength is calculated by testing small-scale prisms in as per ASTM E 518 Test Method or masonry flexural bond strength can be evaluated as per ASTM C 1072 Test Method. Wind, earthquake or eccentric loads acting on masonry walls cause bending about the vertical or horizontal or both the axis, depending upon its geometry. Flexural tension parallel to bed joint (f_{tp}) is produced when bending takes place in horizontal axis. Flexure tension normal to bed joints (f_{tn}) is produced when bending occurs about vertical axis. The modulus of rupture is different for both the planes and the ratio of (f_{tp}) to (f_{tn}) is termed as orthogonal strength ratio R. It represents the degree of anisotropy of the material and is set at 2.0 in masonry codes. However it varies from 1.5 to 8 for clay masonry.

3.7.4 Elastic Modulus

The single most important property of the masonry structure is modulus of elasticity. It gives the stiffness of a masonry building when combined with moment of inertia of the section. For masonry structures it is calculated in the form of secant modulus of elasticity which is corresponding to 33% of ultimate peak compressive strength of masonry.

Chapter 4

Rationale and Scope of Study

The properties of masonry are not very well related to its constituent materials such as unit, mortar, grout and reinforcement. However strength and elastic attributes of brick masonry need to considered for seismic outline. The strength characteristics such as compressive strength, tensile and shear strength are often required in checking design of masonry structures. The modulus of elasticity, Poisson's ratio and damping properties are required for carrying out seismic studies. The majority of houses (about 95%) in flood prone areas are constructed in the brick masonry. The quality of these houses obviously diminishes under the standing water conditions prompting to the crumple of these houses. So this exploration work can be very valuable to give some kind of constraining plan quality to these houses so that these houses can withstand the heaps securely even in the most exceedingly awful conditions.

Chapter 5

Objectives of Study

- Determination of elastic properties of brick masonry after 7 and 28 days at different grades of mortar.
- Determination of various properties of submerged assemblage prototypes at different mortar grades and percentage loss in strength.
- To relate the accuracy of triplet and diagonal shear test.
- To develop the stress-strain curves and load-displacement curves in order to understand the non-linear behaviour of brick masonry structures.
- To relate experimental findings and numerical models.

Chapter 6

Research Methodology

6.1 Materials for masonry construction

6.1.1 Unit cell

A masonry unit is made from concrete, clay or stones. Therefore on the basis of unit used in the masonry construction, it is categorized into brick masonry, stone masonry, block masonry or adobe masonry. The compressive strength of a unit is the maximum stress up to which it can resist the gradual increase in loading acting normal to bedding plane. The compressive strength of a unit is the maximum stress up to which it can resist the gradual increase in loading acting normal to bedding plane. The minimum requirement of masonry unit is specified in IS 4326:1993. Modulus of elasticity of a masonry unit is obtained in the form of secant modulus. It is the slope of the line joining from zero stress to approximately 33% of the unit compressive strength. Tensile strength of unit can be determined by modulus of rupture. Modulus of rupture to compressive strength ratio varies between 0.1 - 0.32. Poisson's ratio is another stiffness index to be needed. Poisson's ratio for ungrouted clay masonry and grouted clay masonry is 0.23 and 0.40 respectively as obtained experimentally.

6.1.2 Mortar

Mortar is a plastic and workable paste used to bind masonry blocks into a structural mass. For various categories of buildings constructed in seismic areas, IS 4326: 1993 has recommended mortar mixture for each category. These categories depend upon the design seismic coefficient (α_h). (category: A ($0.04<\alpha_h<0.05$), B ($0.05<\alpha_h<0.06$), C ($0.06<\alpha_h<0.08$), D ($0.08<\alpha_h<0.12$) and E ($0.12\leq\alpha_h$). For category A buildings, mortar mixture should be M_2 (cement- sand 1:6) or M_3 (lime cinder 1:3) or even richer. M_2 mortar is recommended for the construction of B and C Category type buildings. For D and E type of construction the mortar should be H_2 (cement sand 1:4) or M_1 (cement –sand- lime 1:6:1) or richer.

6.1.2.1 Compressive strength, bond strength and flexural tensile strength

Compressive strength, bond strength and flexural tensile strength are essential properties of the hardened mortar that affect masonry construction. Flexural tensile strength of mortar is generally more than bond strength of mortar. Therefore flexural tensile strength of masonry is governed by the bond strength of mortar to brick. These properties can be determined as:

6.1.2.2 Bond strength of mortar to brick f_b (psi) can be evaluated as:

$$f_b = 0.005[1.8 + (F - 105)^{0.5}](40 - A)(124 - t_m \quad (10)$$

Where "A" gives air content in mortar by volume. It should be less than 30 in terms of percentage. "F" gives the percentage initial flow of mortar. "T_m" gives exposure time of mortar. It is usually less than 120 seconds.

6.1.2.3 Flexural tensile strength f_{tm} (psi) of mortar is determined as:

$$f_{tm} = 1.47 \times 10^{-5} f_c (11700 - f_c) \quad (11)$$

Where f_c represents mortar compressive strength in psi

6.1.2.4 Compressive strength of mortar f_c (psi) is given by:

$$f_c = 3.25 s\alpha\beta T(554\delta + \gamma(130-F) \quad (12)$$

"s" is a constant depending on dimensions of cube, "α" gives mortar curing factor , "β" is air content factor (β= 0.021(57.3-A), T represents plastic mortar age factor [T = 0.029(35-T_p^2), T_p should be less than 4 hours and represents plastic mortar age, δ is mortar type factor; δ = (1+1.46log(C_v/L) and **$\gamma = C_v/L + 3.7$**

Where, C_v/L represents cement- lime ratio by volume in mortar

6.1.3 Grout

Grout is a mixture of Portland cement, sand, gravel and water. It is used to increase the compressive strength of masonry. It is placed in the cores of hollow masonry units or between the solid units to bind the masonry and reinforcing steel into a structural system. IS:4326:1993 has specified the minimum cement concrete grade so as to achieve good bond and corrosion resistance. On the basis of grouting, masonry has different categories and grouted masonry leads to increase in compressive strength.

6.1.4 Reinforcement

Reinforcing steel in masonry has been extensively used in earth quake prone areas. Reinforcing steel provides ductility, toughness and energy absorption characteristics to the structure and that is very necessary in structures subjected to dynamic forces of earth quakes.

Shear and tensile forces generated by dynamic loads are also resisted by reinforcing steel. Reinforced masonry performs well in case a structure is subjected to dynamic loadings like earthquake as it has the sufficient ductility to with stand the load reversals in comparison to plain unreinforced masonry. In India reinforcement is provided in the form of various horizontal bands, and vertical reinforcement at junctions of walls or corners. IS 4326: 1993 specifies the requirement and size of reinforcement in the masonry depending upon the building category.

6.2 Experimental Procedure

To simulate the structural behavior of brick masonry structure, it is essential to calculate the mechanical characteristics of the constituent materials like bricks and mortar. Aspect ratio (height to thickness ratio) of prisms to be used should be in the range of 1.3 and 5 according to ASTM. IS code recommends aspect ratio of at least 2 but should not be more than 5 [23]. Aiming to characterize the compressive, shear and flexural strength of brick masonry, various masonry specimens were made under the guidance of an expert local mason. The mixing of materials for mortar and wetting of bricks have been done in such a way so as to represent the field conditions. The masonry specimen s were stored and cured in the lab. After 48 hours of specimen preparation, curing was started and the specimens were wet cured for minimum of 7 days and tested after 7 and 28 days.

6.2.1 Compressive Strength Testing

The bureau of Indian standard gives some numeric values for basic compressive strength [23]. Due to presence of moisture, drop in compressive strength and stiffness is registered which is influenced by the size of pores [36]. According to MSJC Specifications the "Unit Strength Method" can be used to estimate the masonry compressive strength by considering each constituent material or "Prism Testing Method" is used by testing the properties of masonry assemblage as a whole [37]. Prism testing gives more accurate estimation of masonry compressive strength. It can be carried as per ASTM E 447 Test Methods for the computation of Masonry Prism Compressive Strength. Aspect ratio (height to thickness ratio) of prisms to be used should be in the range of 1.3 and 5 according to ASTM. IS code recommends aspect ratio of at least 2 but should not be more than 5 [23]. The masonry specimens were stored and cured in the lab. The specimens were wet cured for minimum of 7 days and tested after 7 and 28 days. The modulus of elasticity of the individual unit is not generally calculated and is hence not specified in most of the codes. The normalized unit compressive strength was found to be 21.7 MPa. Ordinary Portland cement (43grade) and river sand as per IS specifications were used for the preparation of mortar [38, 39]. The mortar cubes having dimensions of (70×70×70) mm were employed for testing the compressive strength of mortar. The 28 days compressive strength of 1:2, 1:3 and 1:6 grades of mortar was found to be 20.2 MPa, 18.1 MPa and 3.8 MPa respectively. The dimensions of each masonry specimen were set around approximately (108 x 227 x 400) mm [thickness x width x height]. Uniaxial compression test was carried on all the masonry prisms and load was progressing gradually at a controlled rate till specimen fails (0.01 mm/sec). Thickness of mortar joint was kept constant throughout the experimental work around $\frac{3}{8}$ to $\frac{1}{2}$ inches (10-12 mm). Some samples were also kept submerged in water for 24 hours and then tested. Each prism consists of five bricks. Also a thick steel plate is installed at the top between the upper platen of UTM and the masonry specimen as shown in figure 6.1 for the uniform transfer of loading. Almost all the masonry prisms show similar failure patterns i.e.; development of cracks vertically along the height as given in figure 6.2 and figure 6.3.

Fig 6.1: Compression testing

Fig 6.2: Failure pattern

Fig 6.3: Failure pattern

6.2.2 Shear strength testing

The normalized unit brick compressive strength was found to be 21.2 MPa. Ordinary Portland cement (43grade) and river sand as per IS specifications were used for the preparation of mortar[7]. The masonry specimens were stored and cured in the lab. The specimens were wet cured for minimum of 7 days and tested after 28 days. 1:2, 1:3 and 1:6

grades of mortar were employed throughout the research. Some masonry specimens were also submerged in water for 24 hours (saturated) and then tested.

6.2.2.1 Triplet Test: In order to obtain the shear strength of masonry along the bed joint, the dimensions of each masonry triplet were set as (230 x 225 x 100) mm. Iron wedge is used to perform the testing of specimens and it was supported on a supporting platform as shown in Figure 6.4. The apparatus was so arranged that the stress distribution and magnitude remained almost constant on both faces by applying pressure on middle brick. Figure 6.5 shows the failure pattern in triplet tests.

Fig 6.4: Base shear test

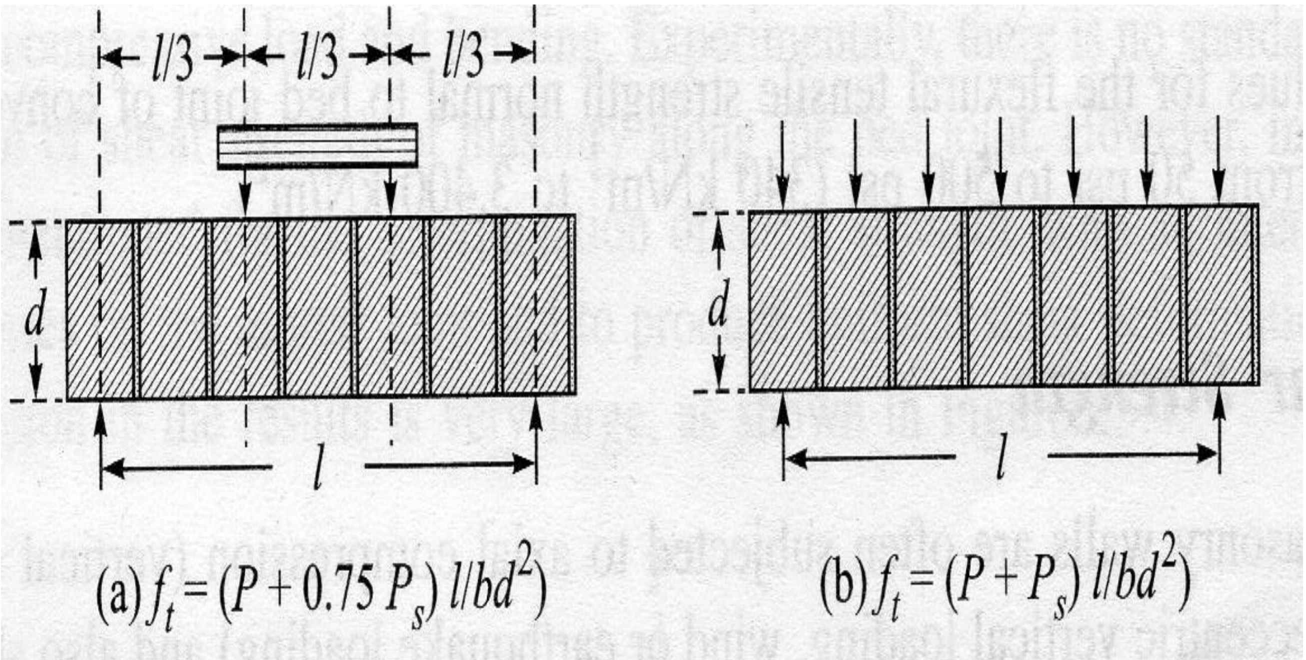
Fig 6.5: Failure pattern

6.2.2.2 Diagonal Compression test: Aiming to obtain the diagonal tensile (shear) strength, masonry specimens with dimensions of (420 x 420 x 210) mm were taken. The specimens were tested after 7 and 28 days with varying mortar grades. The specimens were positioned in such a way that diagonal axis of specimen is in the vertical direction and loaded in compression along the same direction. ASTM standard [ASTM, 2002] recommends two steel loading shoes, which should be fixed on two opposite corners of a masonry specimen, as in shown in Figure 6.6. Transducers were placed on both sides of the specimen to measure lengthening of the horizontal diagonal and shortening of the vertical diagonal. Figure 6.7 shows the failure pattern in diagonal compression test.

Fig 6.6: Diagonal shear test **Fig 6.7: Failure pattern**

6.2.3 Flexural strength testing

For unreinforced masonry, bond strength of masonry in flexure plays an important role in the design considerations. ASTM E 518 recommends two methods for conducting the tests on flexure beams which are termed as beam tests. In method A concentrated loads are applied at 1/3 points of the span and in method B entire beam span is acted upon by uniform loading as illustrated in fig 6.8.



(a) Method A setup. **(b) Method B setup**

Fig 6.8: Flexural tensile strength setups

Method A was adopted in order to perform the flexural tensile strength test. Samples of 1:6 mortar grade fails due to its own weight. Almost all the samples fail due to their own weight except sample of 1:2 mortar grade sample as shown in fig 6.9.

Fig 6.9: Test setup for flexural tensile strength

Chapter 7

Results and Discussion

The main objective of the research was to determine various elastic properties of brick masonry after 7 and 28 days at different grades of mortar and to develop stress-strain curves. Various numerical models of brick masonry are considered in order to relate experimental findings and numerical models. The effect of mortar and brick strength on masonry compressive strength is also studied and the results are compared. Peak strength f'_mvalues of prisms with varying mortar grades are also compared. The compressive testing of masonry assemblages with different mortar grades was carried out on UTM. The stress-strain behavior of different masonry prisms is given in graphical form. Test setup and failure pattern of masonry prisms is given in figures 6.1 to 6.7. The failure pattern of almost all the specimens was similar i.e.; development of cracks vertically along the height as given in fig 6.3. The masonry prisms were constructed with varying grades of mortar. Different grades of mortar employed in the study are 1:2, 1:3 and 1:6. Masonry prism with 1:2 mortar grade (after 7 days) is having 14.95% and 52.75% more capacity in compression as compared to prisms with 1:3 and 1:6 mortar grade respectively. The stress-strain curves of masonry prisms are plotted as shown in figures 7.1.

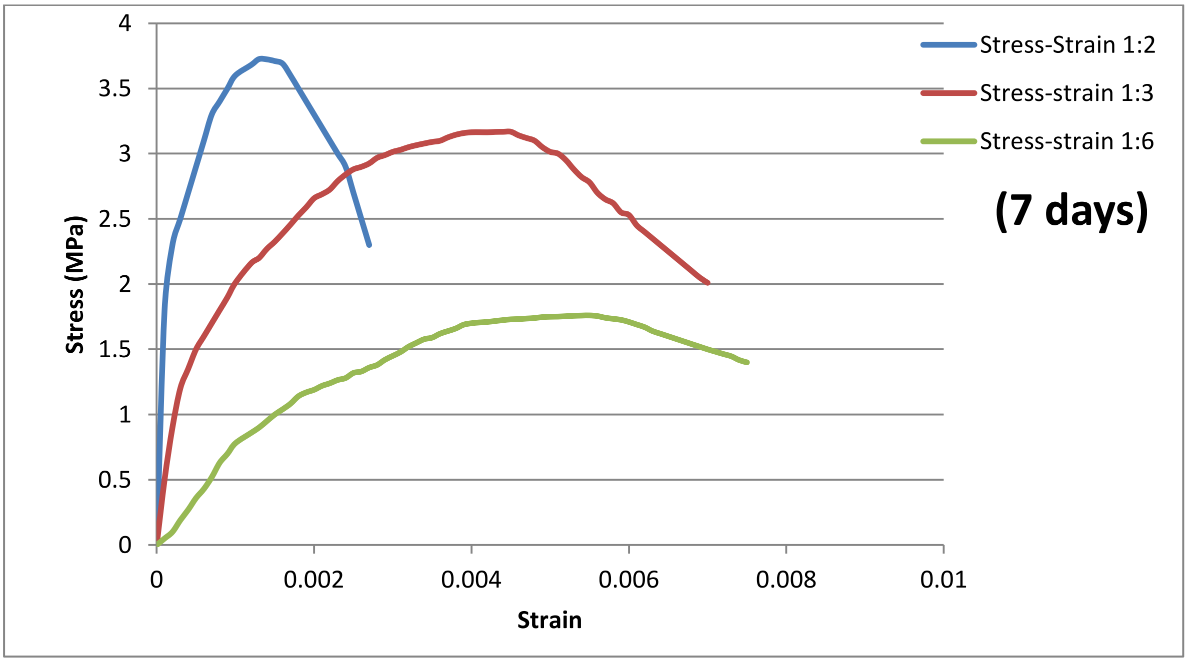


Fig 7.1: Comparison of Stress-Strain curves of masonry prisms at different mortar grades after 7 days

Despite low value of peak strength of prisms with low mortar grades, strain at failure is large in comparison with prisms having richer mortar grades. Failure strain of 1:2, 1:3, and 1:6 masonry prisms after 7 days testing is 0.0025, 0.0068, and 0.0085 respectively. Thus prisms with low mortar grade exhibit a little ductile behavior than prisms with rich mortars as obvious from above stress-strain curves. Therefore masonry structures with richer mortar grades can be made effective when combined with reinforcement which will modify its ductile behavior. Table 7.1 shows ultimate the comparison of masonry compressive strength of different masonry prisms after 7 days of testing as given below:

Table 7.1 Peak masonry compressive strength after 7 days

S.No.	**Mortar Grade**	**Peak masonry compressive strength (MPa)**
1	**1:2**	**3.725**
2	**1:3**	**3.168**
3	**1:6**	**1.76**

In present study, different control points are considered on stress-strain curve in order to define the linear and non-linear characteristics of brick masonry. These different control points are well dependent on type of mortar grade employed in masonry specimens. The stress-strain curve exhibits linear variation only up to $0.33f'_m$. The corresponding modulus of elasticity is termed as secant modulus of elasticity. Cracks start to develop in masonry prisms after $0.33f'_m$. Strain at $0.33f'_m$ for all the specimens is given in table 7.2. Hence it is obvious that in submerged samples cracks develop in mortar and brick bond introducing non-linear behavior at lower loads as compared to unsaturated samples. Another control point on rising limb to be considered is $0.75f'_m$, at this point vertical cracks propagate throughout masonry but there is still resistance to applied loads. Strains in prisms corresponding to $0.75f'_m$ are given in Table 7.2. There is a point on stress-strain curve which represents the behavior of masonry prior to failure and it is taken at $0.9f'_m$. At this point cracks have progressed throughout the masonry prism. For different masonry prisms, strains corresponding to $0.9f'_m$ are given in Table 7.2. The crest or peak on stress-strain curve represents ultimate strength of masonry prism. If load is applied beyond this point, there is no resistance against load. In other words there is drop in load capacity beyond f'_m and abrupt increase in deformations and strain in the masonry prism. In general it has been observed that masonry prisms show linear behavior up to $0.33f'_m$ and cracks start to propagate throughout the specimen at $0.75f'_m$. Descending limb of stress-strain curve shows sudden drop after ultimate peak value reaches (f'_m). Therefore the values corresponding to $0.2f'_m$on falling limb were not recorded. There is abrupt increase in strain which leads to brittle failure of specimen after f'_m has been reached.

Table 7.2 Control points on stress-strain curves

Stress in terms of f'_m	1:2	1:3	1:6	1:2(submerged)	1:3(submerged)	1:6(submerged)
0	0	0	0	0	0	0
0.33	0.0001	0.0003	0.0004	0.000078	0.00027	0.00035
0.75	0.0013	0.0026	0.0031	0.0011	0.0025	0.0028
0.9	0.0027	0.0037	0.0048	0.0026	0.0036	0.0039
1	0.0039	0.0048	0.006	0.00385	0.00478	0.0055

Thus prisms with low mortar grade exhibit a little ductile behavior than prisms with rich mortars as obvious from above stress-strain curve in figure 7.2. Therefore masonry structures with richer mortar grades can be made effective when combined with reinforcement which will modify its ductile behavior. The 28 days capacity of prism in compression with 1:2 mortar is approximately 6.74% and 41.8% more as compared to 1:3 and 1:6 mortar prisms. Masonry prisms submerged in water for 24 hours suffer a considerable loss in strength. The percentage loss of strength in submerged masonry prisms as compared to normal specimens has been found to be around 15% (approx.). The masonry constituents have a natural tendency to absorb water because of presence of pores in bricks and mortar causing increase in dead load of masonry. Therefore after ingress of water in masonry, bond strength diminishes causing loss in strength. So this exploration work can be very valuable to give some kind of constraining plan quality to the houses subjected to floods where the strength under the standing water diminishes.

Table 7.3 gives secant modulus of each prism and it is clear that despite low value of peak strength for prisms with low mortar grades, strain at failure is large in comparison with prisms having richer mortar grades. Failure strains of 1:2, 1:3, 1:6, 1:2(submerged), 1:3(submerged) and 1:6(submerged) have been recorded as 0.005, 0.0071, 0.0085, 0.0046, 0.0066 and 0.0081 respectively.

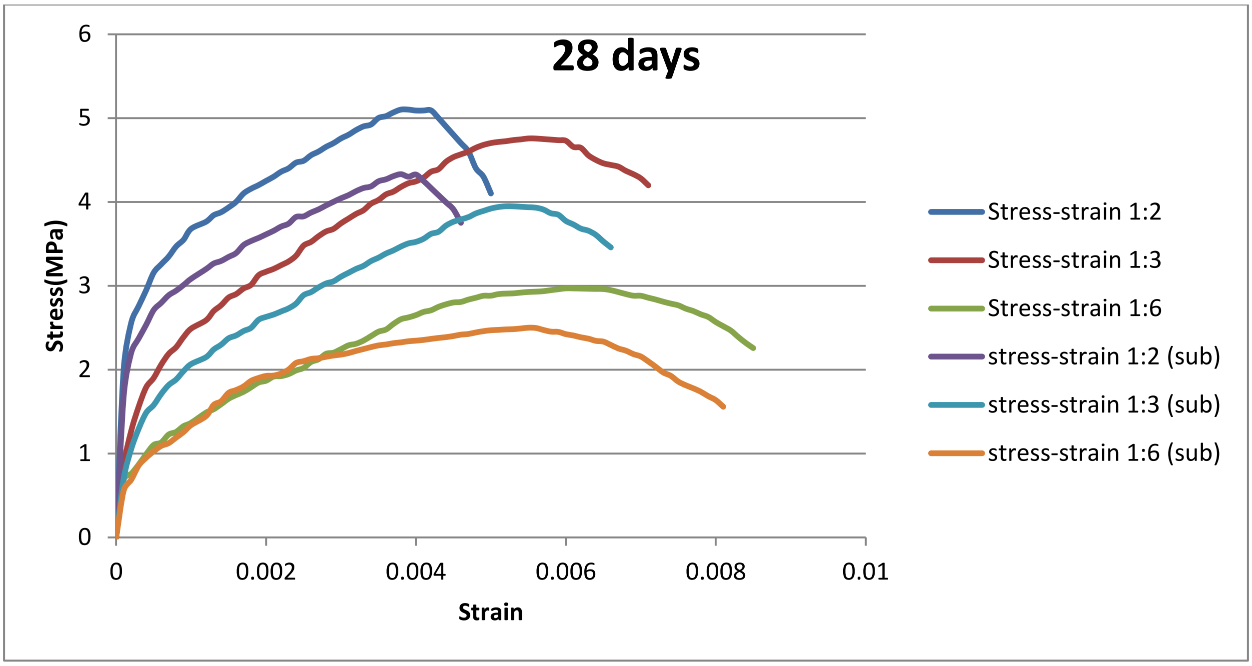


Figure 7.2: Comparison of Stress-Strain curves of masonry prisms at different mortar grades after 28 days

Table 7.3: Failure strain and secant modulus of elasticity

Masonry prism	Peak masonry compressive strength (MPa)	Failure strain	E_m(MPa)
1:2	5.1	0.005	6732.0
1:3	4.756	0.0071	5231.6
1:6	2.968	0.0085	2448.6
1:2 (submerged)	4.33	0.0046	57150.46
1:3 (submerged)	3.947	0.0066	4342.228
1:6 (submerged)	2.498	0.0081	2355.257

It has been observed that 28 days ultimate strength is 26.96% more as compared to 7 days peak strength for 1:2 masonry prism. In other words, 1:2 masonry prism reaches its 73.04% of ultimate compressive strength in 7 days. The 28 days ultimate compressive strength for 1:3 masonry prism is 33% more as compared to its 7 days ultimate value. Therefore it shows a slight lower value i.e.; only 67% of ultimate compressive strength is achieved in 7 days for 1:3 masonry prism after 7 days. For 1:6 masonry prism, ultimate strength is 40.7% more as compared to its 7 days peak value. Hence, 59.3% of ultimate compressive strength is reached in 7 days for 1:6 masonry prisms. Masonry prism with 1:2 mortar grade (after 7 days) is having 14.95% and 52.75% more capacity in compression as compared to prisms with 1:3 and 1:6 mortar grade respectively. The 28 days capacity of prism in compression with 1:2 mortar is approx. 6.74% and 41.8% more as compared to 1:3 and 1:6 mortar prisms. Therefore masonry prisms with richer mortar grades gain maximum strength in first 7 days. Table 7.3 gives ultimate masonry compressive strength of different masonry prisms after 28 days of testing.

Verification of experimental results and numerical model:

In order to compare the experimental results with numerical analysis, various codes have proposed numerical relations. However, in present study following empirical relation is used by assuming that both bricks and mortar contribute equally to overall masonry strength:

$$\boldsymbol{f'_m = 0.275 f'^{(0.5)}_b \times f'^{(0.5)}_j} \qquad \textbf{(13)}$$

The results obtained by using above relation are given in Table 7.4. Also the comparison of present study and previous research work is given in Table 7.4.

Table 7.4: Comparison of experimental results and numerical model

Experimental values (MPa) of present study				**Predicted values, compressive strength (MPa)**		
Type of prism	**f_b**	**f_j**	**f_m**	**Present study**	**MSJC 2002**	**Bennet et al 1997**
1:6	**21.7**	**3.8**	**2.968**	**2.49 (16.1)**	**6.9 (68.7)**	**6.2 (52.2)**
1:3	**21.7**	**18.1**	**4.756**	**5.4 (13.5)**	**6.9 (8.4)**	**6.2 (20.2)**

Figures in the bracket ( ) represent percentage error in experimental and predicted values.

The number of seismic tremor reports expressed out the overwhelming harms done to brick masonry structures. Because of common earthquake tremors, the vast majority of the provincial houses were harmed in fragile fall because of absence of appropriate building design. In triplet tests, middle brick separates out from the rest of prototype assemblage. Therefore a two way shear failure was found along the bed. It can be observed from Table 7.5 that there is approximately 13.19%, 27.20% and 40% decrease in shear strength in case of saturated samples with 1:2, 1:3 and 1:6 mortar grades respectively. Therefore specimens with low mortar grade suffer a maximum loss in shear strength. Strictly from the experimental study, it is found that shear strength of brick masonry is well dependent on mortar grade employed. Thus bond strength majorly influences shear strength of brick masonry.

Table 7.5: Experimental results of masonry triplet test at different mortar grades

Mortar Grade	Peak load (KN) for unsaturated triplets	Peak load (KN) for saturated triplets	Shear Strength (MPa) for unsaturated triplets, Eq. (5)	Shear strength (MPa) for saturated triplets, Eq.(5)
1:2	37.31	32.41	0.811	0.704
1:3	29.27	21.34	0.636	0.463
1:6	12.68	7.59	0.275	0.165

In diagonal compression test, cracks develop in the middle of specimen and progress towards upper and bottom corners through mortar only, without damaging bricks as shown in Figure 6.7. Therefore mortar joint cracking is a common shear failure of masonry. This failure is influenced by properties of both unit bricks and mortar. It is clear from Figure 7.3 that specimens with rich mortars show abrupt and brittle failure without much deformation as compared to specimens with low mortar grades.

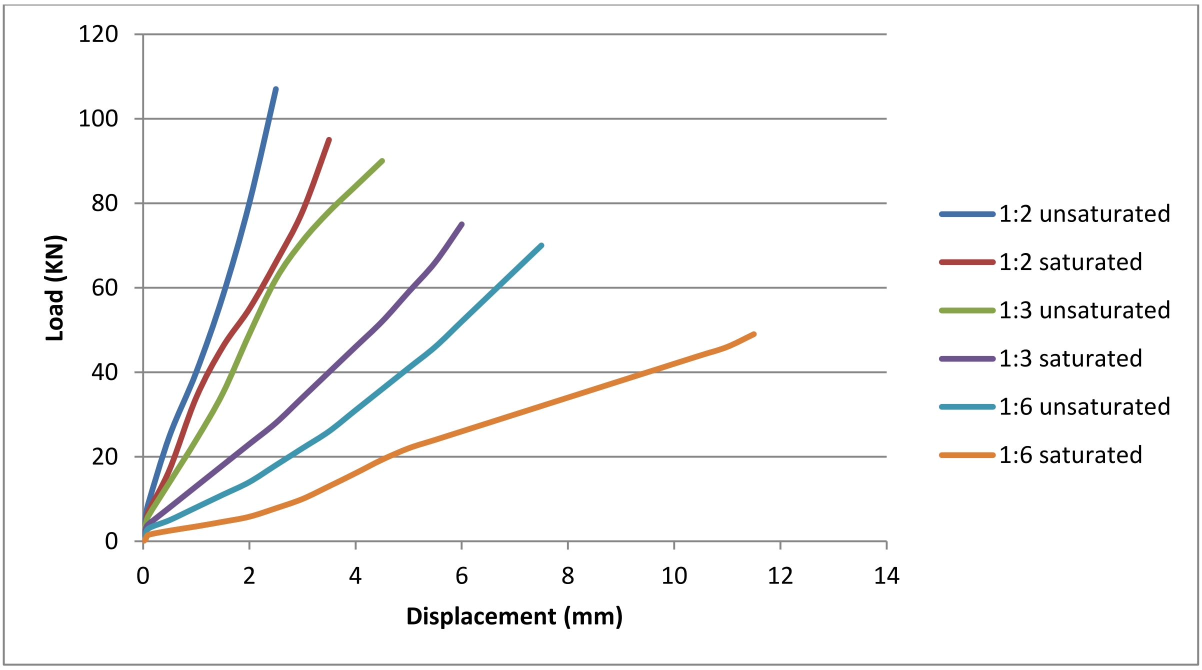


Fig 7.3: Load-Displacement curves (Diagonal Compression Test)

Table 7.6 represents peak load and shear strengths of both saturated and unsaturated specimens using equations (6), (8) and (9). It can be observed from Table 4.6 and Eq. (9) that there is approximately 11.7%, 16.4% and 30.5% decrease in shear strength in case of saturated samples with 1:2, 1:3 and 1:6 mortar grades respectively.

Table 7.6: Diagonal Compression test results of masonry specimens at different mortar grades

Specimens with different mortar grade	Peak Load (KN)	Shear strength (MPa), Eq. (6)	Shear strength (MPa), Eq. (8)	Shear strength (MPa), Eq. (9)
1:2 (unsaturated)	107.66	0.862	0.610	0.402
1:2 (saturated)	95.06	0.761	0.538	0.355
1:3 (unsaturated)	89.48	0.717	0.507	0.334
1:3 (saturated)	74.80	0.599	0.424	0.279
1:6 (unsaturated)	69.27	0.555	0.392	0.259
1:6 (saturated)	48.37	0.387	0.274	0.180

Chapter 8

Conclusion and Future Scope

Conclusions: Experimental findings can be summarized in the form of following conclusions:

- Mortar grade plays an important role in enhancing the capacity of masonry prism structures in compression. Increase in 28 days capacity of rich masonry prisms is slightly less compared 7 days because almost 60-70% of strength is reached in first 7 days. Therefore extreme care should be taken during initial 7 days.
- Masonry prisms submerged in water for 24 hours suffer a considerable loss in compressive strength. The percentage loss of strength in submerged masonry prisms as compared to normal specimens has been found to be around 15% (approx.).
- Despite low peak strength of prisms with low mortar grades, strain at failure is large in comparison with prisms having richer mortar grades. Thus prisms with low mortar grade exhibit a little ductile behavior than prisms with rich mortars as obvious from stress-strain curves. This may be due to the presence of more brittle material (cement) in case of prisms with rich mortar. Ductility can be enhanced by using it in combination with reinforcement.
- In general it was observed that masonry prisms show linear behavior up to $0.33f'_m$ and cracks start to propagate throughout the specimen at $0.75f'_m$. Descending limb of stress-strain curve shows sudden drop after ultimate peak value reaches (f'_m). There is abrupt increase in strain which leads to brittle failure of specimen. Experimental findings are verified by numerical model with lesser percentage error.
- Masonry specimens suffer a major loss in shear strength when subjected to submerged conditions. Thus after ingress of water in masonry, bond strength diminishes causing loss in strength. There is approximately (average) 12%, 21.75% and 35% loss in shear strength in case of saturated specimens with 1:2, 1:3 and 1:6 mortar grades respectively. So this investigation work can be exceptionally profitable to give some sort of constraining plan quality to the houses subjected to floods where the quality under the standing water reduces.
- Although triplet test and diagonal compression test provide slightly different values but the values are well related and close to those provided by Eurocode 6, particularly by Eq. (9). Triplet test is easy to perform and hence preferable but diagonal

compression test is more accurate as numerous equations are available to interpret the experimental results.

Future Scope: As a reasonable other option to tedious lab tests, numerical and analytical techniques have pulled in broad consideration in research group and also in industry. The most comprehensive approach is to model each brick and each mortar joint in the masonry. This can be achieved by the application of finite element technique. Multilayer model, one-step homogenization approach, two-step homogenization method and asymptotic homogenization strategies can be utilized as a part of blend with FEM yet these request concentrated computational endeavours. Neither of them has taken into account the specific pattern of bricks and mortar nor have fully exploited the periodicity of geometry and other field quantities. A micro homogenization technique alleged "Eigen Strain Homogenization Method" can be executed to model brick work structures. Important material properties of the brick work structure will be inferred in light of strain energy approach.

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Appendix

Compression Tests

Readings of sample with Mortar grade 1:2 subjected to testing after 7 days

Stress (MPa)	Strain
0	0
1.8	0.0001
2.3	0.0002
2.5	0.0003
2.7	0.0004
2.9	0.0005
3.1	0.0006
3.3	0.0007
3.4	0.0008
3.5	0.0009
3.6	0.001
3.68	0.0012
3.725	0.0013
3.723	0.0014
3.71	0.0015
3.69	0.0016
3.6	0.0017
3.5	0.0018
3.4	0.0019
3.3	0.002
3.2	0.0021
3.1	0.0022
3	0.0023
2.9	0.0024
2.7	0.0025
2.5	0.0026
2.3	0.0027

Readings of sample with Mortar grade 1:3 subjected to testing after 7 days

Stress (MPa)	Strain
0	0
0.5	0.0001
0.9	0.0002
1.2	0.0003
1.35	0.0004
1.5	0.0005
1.6	0.0006
1.7	0.0007
1.8	0.0008
1.9	0.0009
2.01	0.001
2.16	0.0012
2.2	0.0013
2.27	0.0014
2.325	0.0015
2.389	0.0016
2.456	0.0017
2.526	0.0018
2.589	0.0019
2.658	0.002
2.689	0.0021
2.725	0.0022
2.79	0.0023
2.84	0.0024
2.88	0.0025
2.899	0.0026
2.925	0.0027
2.968	0.0028
2.989	0.0029
3.014	0.003
3.03	0.0031
3.05	0.0032
3.065	0.0033
3.078	0.0034
3.09	0.0035
3.099	0.0036
3.125	0.0037
3.145	0.0038
3.158	0.0039
3.164	0.004
3.1648	0.0041
3.1639	0.0042
3.1668	0.0043

3.1677	0.0044
3.168	0.0045
3.14	0.0046
3.12	0.0047
3.1	0.0048
3.05	0.0049
3.014	0.005
3	0.0051
2.95	0.0052
2.88	0.0053
2.82	0.0054
2.78	0.0055
2.7	0.0056
2.65	0.0057
2.62	0.0058
2.55	0.0059
2.53	0.006
2.45	0.0061
2.4	0.0062
2.35	0.0063
2.3	0.0064
2.25	0.0065
2.2	0.0066
2.15	0.0067
2.1	0.0068
2.05	0.0069
2.01	0.007

Readings of sample with Mortar grade 1:6 subjected to testing after 7 days

Stress (MPa)	Strain
0	0
0.05	0.0001
0.1	0.0002
0.19	0.0003
0.27	0.0004
0.36	0.0005
0.43	0.0006
0.52	0.0007
0.63	0.0008
0.7	0.0009
0.78	0.001
0.86	0.0012
0.9	0.0013
0.95	0.0014

1	0.0015
1.04	0.0016
1.083	0.0017
1.14	0.0018
1.17	0.0019
1.19	0.002
1.22	0.0021
1.24	0.0022
1.265	0.0023
1.28	0.0024
1.319	0.0025
1.33	0.0026
1.36	0.0027
1.38	0.0028
1.42	0.0029
1.45	0.003
1.48	0.0031
1.52	0.0032
1.55	0.0033
1.578	0.0034
1.59	0.0035
1.62	0.0036
1.64	0.0037
1.66	0.0038
1.689	0.0039
1.7	0.004
1.706	0.0041
1.71	0.0042
1.717	0.0043
1.724	0.0044
1.73	0.0045
1.732	0.0046
1.736	0.0047
1.74	0.0048
1.747	0.0049
1.75	0.005
1.751	0.0051
1.754	0.0052
1.757	0.0053
1.759	0.0054
1.76	0.0055
1.755	0.0056
1.742	0.0057
1.734	0.0058
1.726	0.0059

1.71	0.006
1.69	0.0061
1.67	0.0062
1.64	0.0063
1.62	0.0064
1.6	0.0065
1.58	0.0066
1.56	0.0067
1.54	0.0068
1.52	0.0069
1.5	0.007
1.482	0.0071
1.464	0.0072
1.447	0.0073
1.418	0.0074
1.4	0.0075

Readings of samples with Mortar grade (1:2, 1:3, 1:6) subjected to testing after 28 days

1:2 Grade		1:3 Grade		1:6 Grade	
Stress (MPa)	**Strain**	**Stress (MPa)**	**Strain**	**Stress (MPa)**	**Strain**
0	0	0	0	0	0
2	0.0001	0.84	0.0001	0.686752	0.0001
2.555546	0.0002	1.265556	0.0002	0.756478	0.0002
2.756445	0.0003	1.556667	0.0003	0.866544	0.0003
2.945681	0.0004	1.788025	0.0004	0.990096	0.0004
3.154426	0.0005	1.899	0.0005	1.100758	0.0005
3.254469	0.0006	2.057788	0.0006	1.129999	0.0006
3.346887	0.0007	2.186666	0.0007	1.224688	0.0007
3.467552	0.0008	2.26677	0.0008	1.256666	0.0008
3.548889	0.0009	2.388555	0.0009	1.325677	0.0009
3.678859	0.001	2.488222	0.001	1.365237	0.001
3.763333	0.0012	2.58866	0.0012	1.486677	0.0012
3.839999	0.0013	2.69677	0.0013	1.525789	0.0013
3.876289	0.0014	2.766889	0.0014	1.586677	0.0014
3.933333	0.0015	2.858889	0.0015	1.651972	0.0015
3.999778	0.0016	2.899999	0.0016	1.695666	0.0016
4.1	0.0017	2.966688	0.0017	1.734678	0.0017
4.156667	0.0018	3.009999	0.0018	1.788889	0.0018
4.199911	0.0019	3.124899	0.0019	1.845555	0.0019
4.250006	0.002	3.166667	0.002	1.866681	0.002
4.299444	0.0021	3.199999	0.0021	1.915666	0.0021
4.358889	0.0022	3.244466	0.0022	1.921667	0.0022
4.399913	0.0023	3.288999	0.0023	1.945666	0.0023

4.467778	0.0024	3.35779	0.0024	1.988977	0.0024
4.489222	0.0025	3.477778	0.0025	2.019245	0.0025
4.555967	0.0026	3.522222	0.0026	2.089999	0.0026
4.599881	0.0027	3.589999	0.0027	2.122222	0.0027
4.655556	0.0028	3.646666	0.0028	2.187779	0.0028
4.7	0.0029	3.677788	0.0029	2.201555	0.0029
4.756644	0.003	3.744444	0.003	2.243651	0.003
4.799889	0.0031	3.79999	0.0031	2.288888	0.0031
4.855573	0.0032	3.855578	0.0032	2.307766	0.0032
4.899878	0.0033	3.899999	0.0033	2.345556	0.0033
4.922222	0.0034	3.977777	0.0034	2.398878	0.0034
5	0.0035	4.02222	0.0035	2.451657	0.0035
5.022222	0.0036	4.08888	0.0036	2.477777	0.0036
5.066667	0.0037	4.122222	0.0037	2.544499	0.0037
5.1	0.0038	4.177788	0.0038	2.599958	0.0038
5.1	0.0039	4.222222	0.0039	2.622222	0.0039
5.088889	0.004	4.244467	0.004	2.64949	0.004
5.089	0.0041	4.287799	0.0041	2.686868	0.0041
5.091111	0.0042	4.358888	0.0042	2.706669	0.0042
5	0.0043	4.388888	0.0043	2.747778	0.0043
4.9	0.0044	4.477777	0.0044	2.777778	0.0044
4.8	0.0045	4.533333	0.0045	2.799924	0.0045
4.7	0.0046	4.566899	0.0046	2.806656	0.0046
4.6	0.0047	4.599999	0.0047	2.834444	0.0047
4.4	0.0048	4.645222	0.0048	2.856667	0.0048
4.3	0.0049	4.678888	0.0049	2.879999	0.0049
4.1	0.005	4.701111	0.005	2.881037	0.005
		4.714566	0.0051	2.899999	0.0051
		4.723388	0.0052	2.905669	0.0052
		4.736666	0.0053	2.908889	0.0053
		4.745011	0.0054	2.917779	0.0054
		4.756111	0.0055	2.925459	0.0055
		4.755103	0.0056	2.928888	0.0056
		4.748661	0.0057	2.934688	0.0057
		4.742222	0.0058	2.946667	0.0058
		4.735555	0.0059	2.957778	0.0059
		4.728811	0.006	2.968542	0.006
		4.655555	0.0061	2.967658	0.0061
		4.64448	0.0062	2.965868	0.0062
		4.55488	0.0063	2.963555	0.0063
		4.5	0.0064	2.961599	0.0064
		4.46	0.0065	2.960423	0.0065
		4.44	0.0066	2.946555	0.0066
		4.42	0.0067	2.924488	0.0067
		4.37	0.0068	2.900556	0.0068
		4.33	0.0069	2.880777	0.0069

		4.28	0.007	2.879929	0.007
		4.197	0.0071	2.856664	0.0071
				2.834559	0.0072
				2.808866	0.0073
				2.786554	0.0074
				2.765888	0.0075
				2.726656	0.0076
				2.697886	0.0077
				2.658869	0.0078
				2.626687	0.0079
				2.566657	0.008
				2.516655	0.0081
				2.465588	0.0082
				2.388876	0.0083
				2.317778	0.0084
				2.255905	0.0085

Readings of submerged samples with Mortar grade (1:2, 1:3, 1:6) subjected to testing after 28 days

1:2 Grade		1:3 Grade		1:6 Grade	
Stress (MPa)	**Strain**	**Stress (MPa)**	**Strain**	**Stress (MPa)**	**Strain**
0	0	0	0	0	0
1.68	0.0001	0.6972	0.0001	0.5555556	0.0001
2.197776	0.0002	1.0504	0.0002	0.6844889	0.0002
2.370543	0.0003	1.29359	0.0003	0.8548886	0.0003
2.533286	0.0004	1.484061	0.0004	0.9486667	0.0004
2.709	0.0005	1.57617	0.0005	1.0244444	0.0005
2.795	0.0006	1.707964	0.0006	1.0888888	0.0006
2.8856	0.0007	1.814933	0.0007	1.1222222	0.0007
2.941	0.0008	1.881419	0.0008	1.1888867	0.0008
3.009	0.0009	1.982501	0.0009	1.2554489	0.0009
3.0828	0.001	2.065224	0.001	1.3377778	0.001
3.1988	0.0012	2.148588	0.0012	1.4455488	0.0012
3.263999	0.0013	2.238319	0.0013	1.5777733	0.0013
3.294846	0.0014	2.296518	0.0014	1.6223331	0.0014
3.343331	0.0015	2.372878	0.0015	1.7222222	0.0015
3.389167	0.0016	2.406999	0.0016	1.7556688	0.0016
3.485	0.0017	2.459388	0.0017	1.7989898	0.0017
3.533167	0.0018	2.498299	0.0018	1.8655688	0.0018
3.569992	0.0019	2.593667	0.0019	1.8999979	0.0019
3.612505	0.002	2.628334	0.002	1.9244444	0.002
3.654527	0.0021	2.655999	0.0021	1.9284578	0.0021
3.705056	0.0022	2.692907	0.0022	1.9524888	0.0022
3.739926	0.0023	2.729869	0.0023	2.0000992	0.0023
3.81995	0.0024	2.78663	0.0024	2.0788889	0.0024
3.82686	0.0025	2.886556	0.0025	2.0999999	0.0025
3.872572	0.0026	2.923444	0.0026	2.1266558	0.0026

3.909899	0.0027	2.979699	0.0027	2.1355466	0.0027
3.957223	0.0028	3.026733	0.0028	2.1522336	0.0028
4.00064	0.0029	3.052564	0.0029	2.1675568	0.0029
4.043147	0.003	3.107889	0.003	2.1788889	0.003
4.079906	0.0031	3.153992	0.0031	2.1966888	0.0031
4.127237	0.0032	3.20013	0.0032	2.2222556	0.0032
4.164896	0.0033	3.236999	0.0033	2.2445889	0.0033
4.184381	0.0034	3.293599	0.0034	2.2677778	0.0034
4.245125	0.0035	3.33442	0.0035	2.2881111	0.0035
4.268889	0.0036	3.38377	0.0036	2.2989778	0.0036
4.306667	0.0037	3.421444	0.0037	2.3145688	0.0037
4.329889	0.0038	3.467564	0.0038	2.3245555	0.0038
4.3	0.0039	3.504444	0.0039	2.3377666	0.0039
4.325556	0.004	3.522908	0.004	2.3444444	0.004
4.25	0.0041	3.558873	0.0041	2.3533355	0.0041
4.165	0.0042	3.617877	0.0042	2.3654888	0.0042
4.08	0.0043	3.642778	0.0043	2.3769899	0.0043
3.995	0.0044	3.716555	0.0044	2.3866666	0.0044
3.91	0.0045	3.762667	0.0045	2.3999999	0.0045
3.75	0.0046	3.790526	0.0046	2.4164444	0.0046
		3.817999	0.0047	2.4244666	0.0047
		3.862266	0.0048	2.4426667	0.0048
		3.891777	0.0049	2.4577778	0.0049
		3.920412	0.005	2.4688444	0.005
		3.938359	0.0051	2.4732102	0.0051
		3.947572	0.0052	2.4787788	0.0052
		3.946735	0.0053	2.4818878	0.0053
		3.941389	0.0054	2.4899577	0.0054
		3.936044	0.0055	2.498899	0.0055
		3.930511	0.0056	2.495666	0.0056
		3.908313	0.0057	2.4724559	0.0057
		3.864111	0.0058	2.4522444	0.0058
		3.845682	0.0059	2.448886	0.0059
		3.772256	0.006	2.4222222	0.006
		3.7305	0.0061	2.4065555	0.0061
		3.68076	0.0062	2.3846422	0.0062
		3.65589	0.0063	2.3684655	0.0063
		3.60615	0.0064	2.3424588	0.0064
		3.5275	0.0065	2.3333334	0.0065
		3.45693	0.0066	2.2933334	0.0066
				2.2516844	0.0067
				2.2255554	0.0068
				2.1848888	0.0069
				2.155888	0.007
				2.096645	0.0071
				2.0322222	0.0072
				1.9648778	0.0073
				1.9254569	0.0074
				1.8565657	0.0075
				1.8123356	0.0076
				1.7766549	0.0077
				1.7355456	0.0078
				1.6823599	0.0079
				1.635555	0.008

Shear Test

Readings of samples (unsaturated) with different mortar grades subjected to testing after 28 days

1:2 Grade		1:3 Grade		1:6 Grade	
Load (KN)	Disp. (mm)	Load (KN)	Disp. (mm)	Load (KN)	Disp. (mm)
0	0	0	0	0	0
6	0.05	4	0.05	1	0.05
9	0.1	6	0.1	3	0.1
25	0.5	14	0.5	5	0.5
40	1	24	1	8	1
58	1.5	35	1.5	11	1.5
80	2	49	2	14	2
107	2.5	62	2.5	18	2.5
		71	3	22	3
		78	3.5	26	3.5
		84	4	31	4
		90	4.5	36	4.5
				41	5
				46	5.5
				52	6
				58	6.5
				64	7
				70	7.5

Readings of samples (saturated) with different mortar grades subjected to testing after 28 days

1:2 Grade		1:3 Grade		1:6 Grade	
Load (KN)	Disp. (mm)	Load (KN)	Disp. (mm)	Load (KN)	Disp. (mm)
0	0	0	0	0	0
4	0.05	3	0.05	0.5	0.05
7	0.1	4	0.1	1.5	0.1
17	0.5	8	0.5	2.5	0.5
34	1	13	1	3.5	1
46	1.5	18	1.5	4.6	1.5
55	2	23	2	5.8	2
66	2.5	28	2.5	7.8	2.5
78	3	34	3	10	3
95	3.5	40	3.5	13	3.5

46	4	16.1	4
52	4.5	19.3	4.5
59	5	22	5
66	5.5	24	5.5
75	6	26	6
		28	6.5
		30	7
		32	7.5
		34	8
		36	8.5
		38	9
		40	9.5
		42	10
		44	10.5
		46	11
		49	11.5