BOND STRENGTH MEASUREMENTS FROM AN AUSTRALIAN STANDARD BOND WRENCH AND ASTM E518 BOND WRENCH

A Thesis

by

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ABSTRACT

Flexural bond strength is a significant factor that governs the mortar to brick bond performance under different loading conditions for masonry walls and columns. Bond testing is a fairly recent addition to the masonry designer's tool box, with the dominant test over the last 150 years being the compression test. Several methods have been developed to test the masonry bond, with the bond wrench from Australia being one of the simpler tests to perform on a masonry stack.

The original bond wrench evolved from the beam tests, as outlined in ASTM E518, with the aim of improving the statistical information measured from the manufactured masonry prisms. There have been different bond wrenches developed in Australia and the USA. Four bond wrenches have been studied in the last decade at TAMU, termed the ASTM Wrench, the Australian Wrench, the TAMU Balanced Wrench and the TAMU Unbalanced Wrench. An extensive set of results shows a difference exists in the bias and precision results for standard masonry prisms tested with different wrenches.

This study's aim is to compare the Australian Bond Wrench results to the ASTM E518 Beam Test results to gain an understanding of the statistical properties for the results from the different tests. The tests used a standard Western King sized clay brick manufactured in Texas.

A total of fifty masonry prisms were built and tested in the same weather conditions. Each prism consisted of six bricks with five joints, and the mortar used was 1:1:6 with Portland cement to lime to sand. Each test group had 25 replicates.

The results show that the mean flexural strength values of Australian Bond Wrench were determined to be statistically higher than ASTM E518 beam mean flexural strength values. A reasonable conclusion is that results obtained using ASTM E518 were low because the results reflect the failure in a weaker joint in the prism and not average results for all joints. The Australian Bond Wrench measures the capacity of each joint in the prism. Further research can be conducted with the use of Texan red brick. Other bond wrenches can be compared with these methods to analyze the presence of bias between the different results.

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NOMENCLATURE

The following contains a term associated with the masonry testing. This term is:

ASTM: American Society for Testing Machines.

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CHAPTER I

INTRODUCTION

BACKGROUND

The structure of the thesis is Chapter I, Introduction, Chapter II, Literature Review, Chapter III, Methodology, Chapter IV, Results, and Chapter V, Conclusions. This chapter outlines the problem statement, hypothesis and limitations of the research work.

Among the various factors that contribute to robust masonry walls and columns, the bond strength between the mortar and masonry units is generally considered one of the important factors. Measurement of the bond strength is a challenging experimental task because of the nature of construction of masonry walls and the need to develop a simple test to approximate the wall results.

This work reviews the bond strength difference in the reported statistical results for the Australian standard bond wrench and the ASTM E 518 Test Procedure for fifty prisms constructed from western King size bricks manufactured in Texas.

PROBLEM STATEMENT

Four bond wrench designs exist at the present time, the American Wrench, the Australian Wrench and the two TAMU designed wrenches. Several previous studies at TAMU have shown a bias exists between some of the wrenches. An older method for testing the bond is the beam test, where a set of point loads are applied to a masonry prism laid sideways between pinned supports. This current work compares the measured bond results from the Australian Bond Wrench to the older ASTM E 518 Beam Test.

This work aims to complete a statistical study on the mean strength results of ASTM E518 beam test and Australian bond wrench to determine if a bias exists between the results. The second aim is to explain the cause of the bias if it exists.

RESEARCH OBJECTIVE

The main objective of the study is to measure mean bond strengths and modes of failure using two test methods, the ASTM E518 Beam Test (ASTM International, 2010) and Australian Bond wrench, for fifty prisms manufactured using a western King size brick and a 1:1:6 cement to lime to sand mortar. If the results show a bias between the two data sets the reasons for this bias will be reviewed.

RESEARCH HYPOTHESIS

For a given set of masonry prisms manufactured using standard conditions and materials, a statistically measureable bias exists between the measured bond results for an ASTM E518 Beam Test and the Australian Bond Wrench.

RESEARCH LIMITATIONS

The study is limited to:

- Testing of only 50 prisms
- 25 prisms will be tested with the ASTM E518 beam test
- 25 prisms will be tested with the Australian bond wrench
- Type I Portland cement will be used for the manufacture of the mortar

- Mortar shall be proportioned by volume as 1:1:6, Portland cement to Hydrated Lime to Sand.
- Test protocol will include random assignment of a test to each prism

SIGNIFICANCE OF STUDY

The significance of the study is that it will help comprehend statistical differences observed between the different methods of bond strength measurement.

CHAPTER II

LITERATURE REVIEW

INTRODUCTION

The literature review outlines the development of the different tests used to measure the bond strength and reviews the results obtained previously for the bond wrench tests. The bond wrench derives from the beam test as developed by Hughes and Zsembery (1980) in Australia. The mechanical test developed by these researchers has been replaced by hand powered tests.

Sugo (2000) followed Baker (1914) in studying the tensile strength of mortar on masonry cylinders. This is a very time consuming work method and not one recommended for daily use on a construction site, although the bond wrench does meet the criteria for ease of use and robustness.

There were various tests that followed the initial tensile strength test performed by Baker (1914). These tests included the couplet test using through bolts, direct tension tests such as the crossed brick couplet test and well known flexural test like Wallette test, Bridge Pier Test, and the latest developed AS3700 bond wrench (Australian Standards, 2001). These tests use different setups and have their own benefits and drawbacks (Khalaf, 2005).

A brief outline of the test methods follows in this chapter.

CROSSED BRICK COUPLET TEST

The crossed brick test has been used for many years. The test uses a direct tensile test that is performed on a pair of crossed bricks separated by a mortar joint. The test involves application of compressive loads on the bars upright as illustrated in Figure 1. The test method “C 321” was originally published in 1954 and was the first ASTM standard that was used to test bond strength of chemical mortars (Portland Cement Association, 1994a).

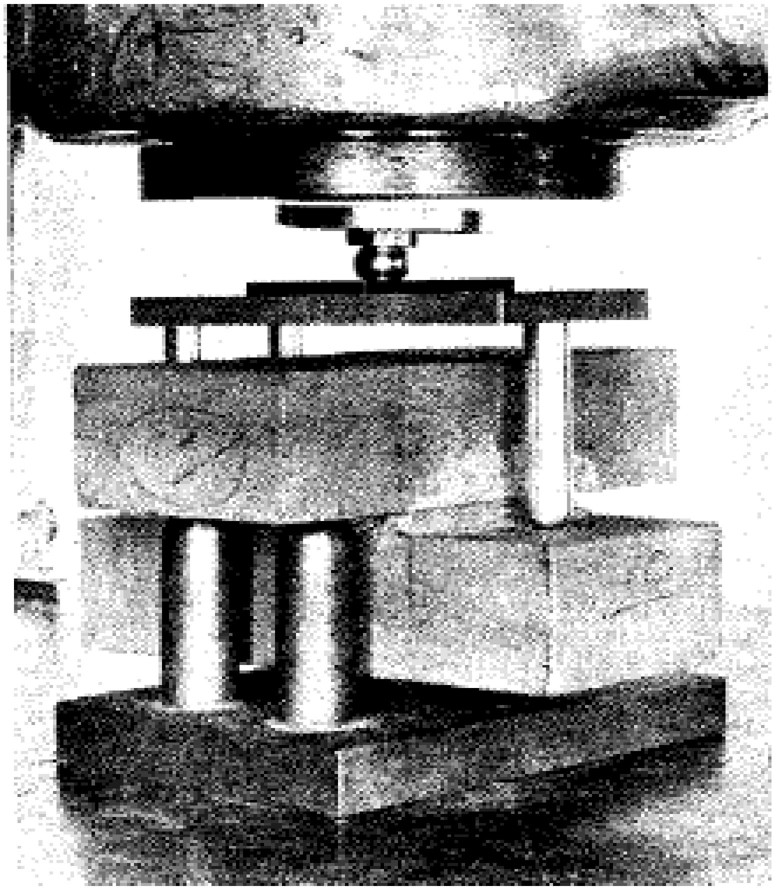


Figure 1: Crossed couplet tests

The corners of the composite interface are under higher stresses causing non-uniformity of tensile stresses over the joint. These areas, which are under high stresses, are prone to variability in preparation when under shrinkage stresses and construction causing scattered results (Portland Cement Association, 1994a). Inserting strips of high-density insulation board interlayers between the test apparatus and test specimen can improve reproducibility of test results.

The test is slow and expensive.

COUPLET BRICK WITH BOLTS THROUGH HOLES

In this test, the application of load is carried out with the help of transverse bolts and steel plates. Brick cavities are first drilled in the specimens and bolts are inserted in them. Typically, localization of holes is at a distance of one quarter of the brick length from the extreme points and half the brick height. The bolt diameter of the testing apparatus determines the variation in the distribution of the maximum tensile stress across the mortar joint, provided the calculation for the tested bond strength includes suitable stress concentration factor (Riddington, Jukes, & Morrell, 1998). There are various advantages of this test like easy administration, less time consumption in performance and consistent results, compared to the previous test. The difference noticed in the edge of the mortar will not greatly influence the result produced when provided with a stiff bolt since the peak stress develops at the side of the unit. This makes sure the stress does not fall off rapidly towards the center, refer to Figure 2.

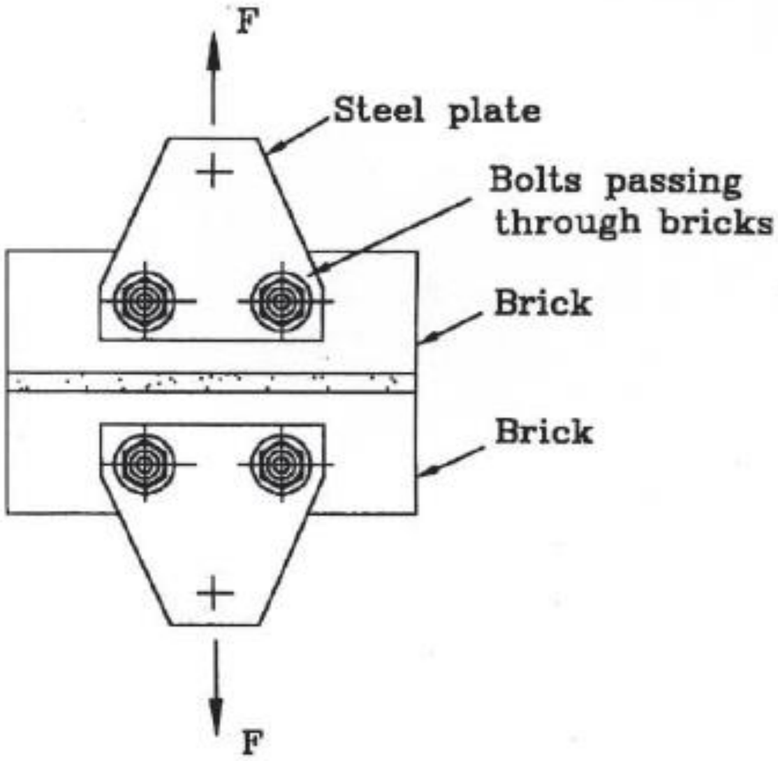


Figure 2: Bolt through holes test from Riddington et al. (1998)

WALLETE TEST

The British Standard 5628 is a recognized standard for the wallette test (British Standards Institution, 1992). The test utilizes four-point loading to derive masonry bed joints' flexural bond strength. The test is cumbersome to perform because of the size of the specimen needed and testing setup (Khalaf, 2005). According to the BS 5628 specifics, the Wallette must be free from frictional restraint. This can be ensured by setting it on two layers of polytetrafluroethylene (PTFE) or on needle or roller bearings or ball (British Standards Institution, 1992). Figure 3 shows the test method.

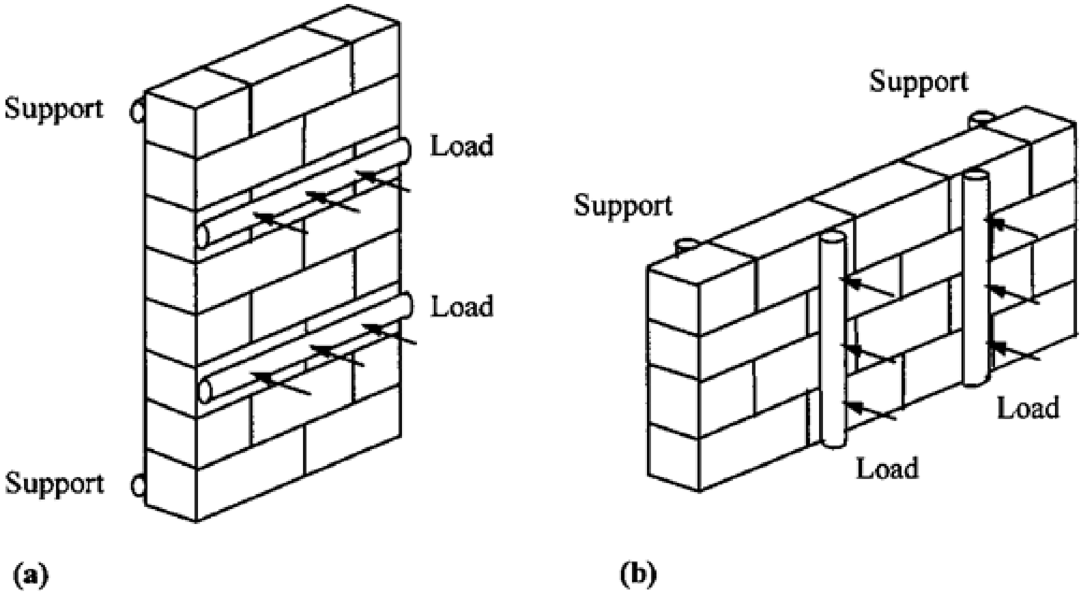


Figure 3: Brick Wallette testing in BS 5628-1:1992

BRIDGE PIER TEST (BOND BEAM)

This test was adopted as the standardized ASTM test method ASTM E 518 in 1974 (Portland Cement Association, 1994a). Jukes and Riddington used the Finite Element Package known as ANSYS to perform a finite element analysis and modeled the bridge pier test as set forth in ASTM E518-80. The test was "*assured of giving a maximum tensile stress matching*" simple bending theory as indicated by their results. The effort to produce masonry specimen and test results as well as the quantity of materials used made the test uneconomical (Riddington et al., 1998). But, this method provides simplified flexural bond strength for the purpose of checking the quality of the job (constituents and workmanship) or developed with different types of mortar and masonry units.

ASTM E 518 has been entitled as the “Standard Test Method for Flexural Bond Strength of Masonry”. It is applied on a stacked bond masonry prism loaded uniformly or at two points. The testing and fabrication of specimens for both the tests is easy. Hence, they are used widely in the industry (Radcliffe, Bennett, & Bryja, 2004). Figure 4 shows the beam tests from the ASTM standard.

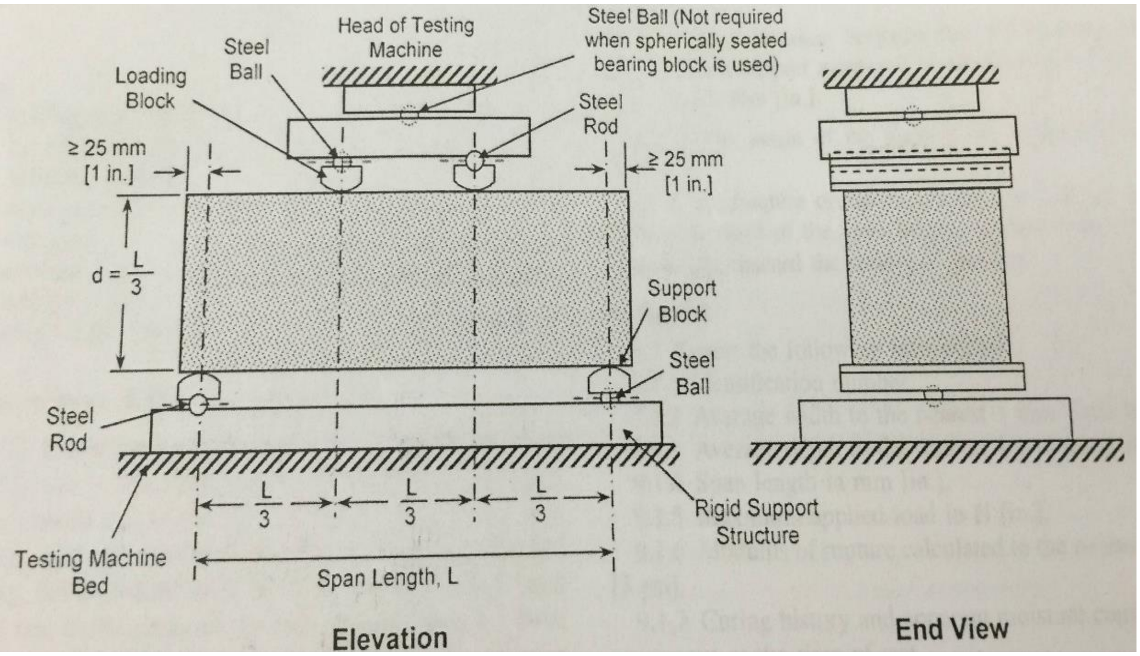


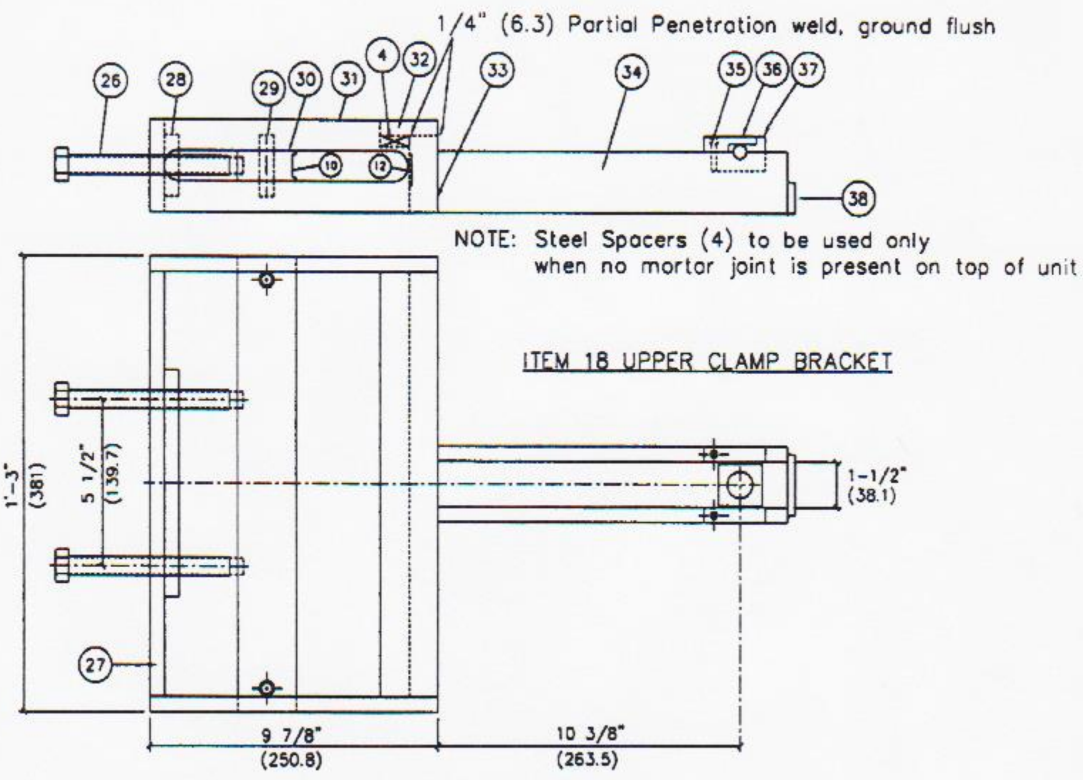
Figure 4: ASTM E518 beam test setup

BOND WRENCH ALTERNATIVES

The ASTM C 1072 and AS 3700 bond wrench test were designed to overcome the shortcomings of the brick pier test. The test specimen in the bond wrench gives more data on testing each joint within the specimen. These tests allow more accurate bias data (Samarasinghe, 1999). It was found by McGinley (1996) that the proposed linear distribution differed from existing strain distribution when it was tested against standard flexural theory. Strain distribution became more pronounced because of an increase in the axial stress percentage relative to the peak flexural stress.

A finite element analysis review of various masonry bond tests concluded that bond wrench test has the capability to produce a simple bending-theory stress distribution (Riddington et al., 1998). It was observed that appropriate attention had to be given to ensure that the obtained stress distribution was not adversely affected by the wrench not being of full length as the specimen tested or the clamping mechanisms used. The test theoretically leads to an unbalanced stress distribution across the cross-section of the prism. This unbalanced stress distribution is composed of a linear flexural stress distribution and a uniform axial compressive stress distribution across the cross-section of the prism.

Bond wrench test was further modified and used by various researchers (Radcliffe et al., 2004). A pure couple bond wrench apparatus was created to counter the undesired compressive forces needed to create an unbalanced stress distribution with the use of ASTM C1072 testing standard (Radcliffe et al., 2004). Figure 5 shows an illustration of the bond wrench arrangement for the American Wrench.



NOTE: Steel Spacers (4) to be used only
when no mortar joint is present on top of unit

ITEM 18 UPPER CLAMP BRACKET

FIG. A3.3 Material List and Detail Drawings

Figure 5: ASTM C1072 bond wrench clamp bracket

Several studies have been completed at TAMU and elsewhere into the effectiveness and results for different wrenches, (Chaudhari, 2010; McGinley, 1996; McHargue, 2013; J. M. Nichols, 2013; J. M. Nichols & N.L. Holland, 2011). The results show the problem of not having a single world standard for such an important test.

ASTM E 518 and AS 3700 are the most used methods for measurement of bond strength. Figure 6 shows the main unit in the Australian bond wrench.

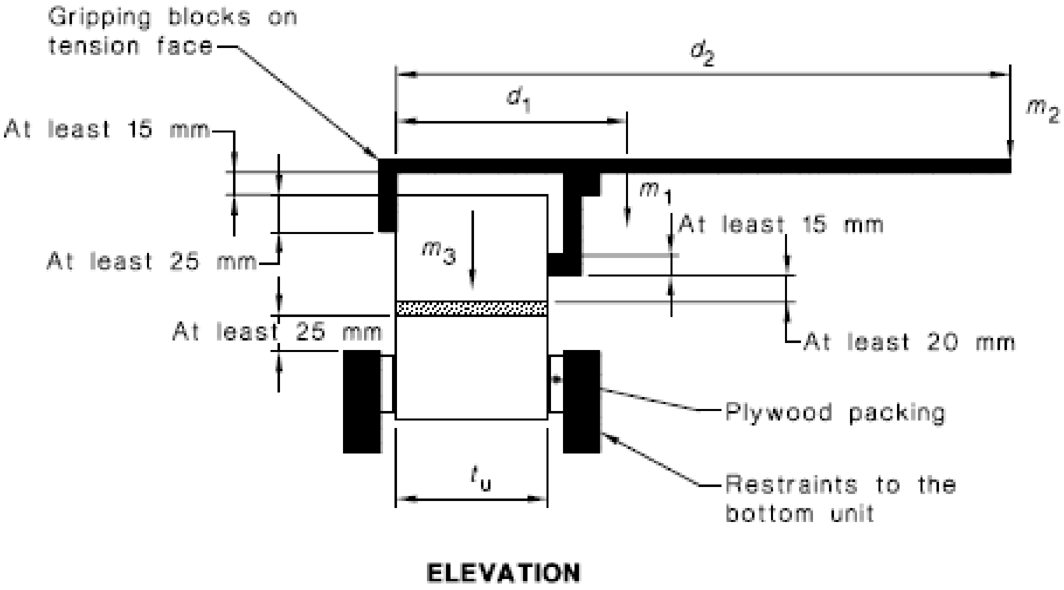


Figure 6: AS 3700 bond wrench test set up

MODIFIED BOND WRENCH

In 2004, the pure couple bond wrench was developed using the ASTM 1072 (Radcliffe et al., 2004). Figure 7 shows the pure couple bond wrench setup. This bond wrench was created to counter the undesired compressive forces in order to create unbalanced stress distribution. The weight of the clamping mechanism is only the compressive load. This is ensured by the mutual negation of the upward and downward testing load. Hence, the vertical forces sum up to be zero.

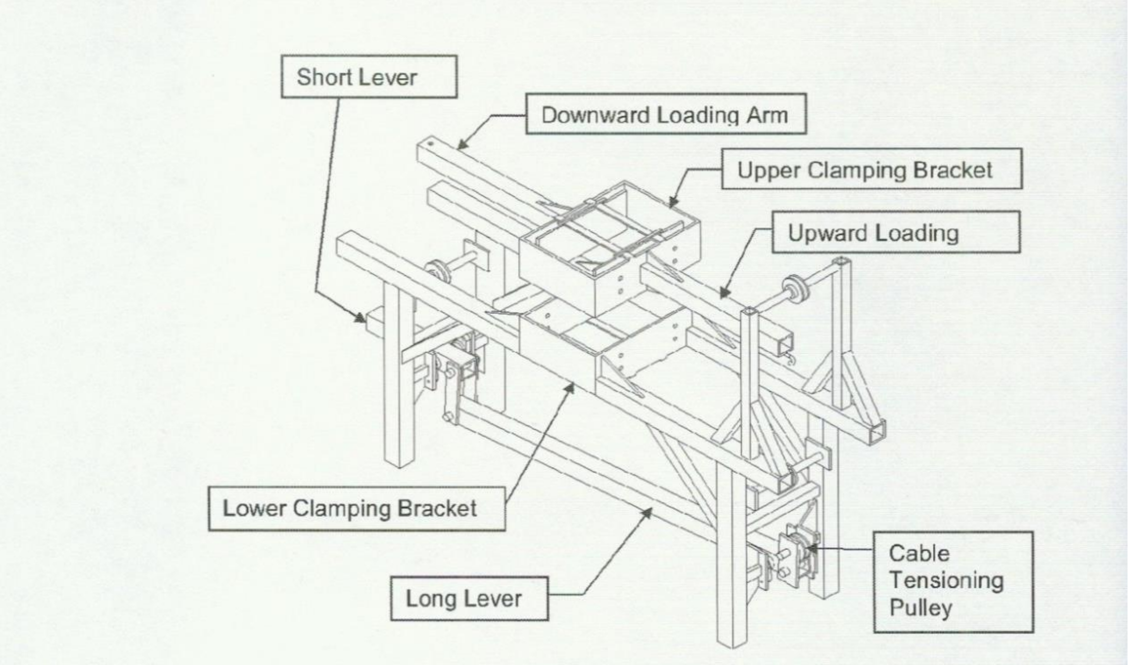


Figure 7: Pure couple bond wrench by Radcliffe et al. (2004)

In case of the American bond wrench, before the external load is applied a moment is created which makes it have high negative attribute as compared to Australian bond wrench (J. M. Nichols, 2013). This induced moment varies with the center of gravity and the mass of the bond wrench. During research on soft mortars, a group of Italians discovered the concept of a balanced bond. The wrench developed was in lines with well know conceptual ideas (Radcliffe et al., 2004).

Figure 8 illustrates the balanced wrench developed by Chaudhari (2010), which imparts zero moment to the top of the prism at the start of the test. Figure 9 shows the unbalanced bond wrench developed by the same team.

Figure 8: TAMU balanced bond wrench by Chaudhari (2010)

Figure 9: TAMU unbalanced bond wrench by Chaudhari (2010)

The self-weight of the wrench along with the center of gravity generates unbalanced stress that gets cancelled by the counter balance extension that is opposite to the apparatus's loading arm. Test conducted on this bond wrench consisted of Texas clay brick and a mortar mix of 1:1:6. The observed results showed a difference in the flexural results between the two wrenches. The test results containing stress values were statistically analyzed with Student's t Test with an acceptance level of 5%. The flexural values obtained from the unbalanced and balanced wrench comparison henceforth were in the range of 0.65 MPa – 0.73MPa. These results have been illustrated in Table 1.

Table 1:

Balanced to unbalanced test results (J. M. Nichols & N. L. Holland, 2011)

Flexural Strength (MPa)	Unbalanced Bond Wrench		Balanced Bond Wrench	
	Researcher I	Researcher	Researcher I	Researcher II
	0.762	0.813	0.472	0.661
	0.773	0.533	0.579	0.701
	0.645	0.813	0.740	0.472
	0.533	0.690	0.691	0.759
	0.706	0.730	0.759	0.691
	0.645	0.794	0.722	0.661
	0.813	0.794	0.661	0.722
	0.832	0.533	0.638	0.759
	0.773	0.832	0.661	0.606
	0.705	0.730	0.691	0.472
Mean (μ)	0.72	0.73	0.66	0.65
Standard	0.09	0.11	0.08	0.10
COV	0.13	0.15	0.13	0.16

An experiment was conducted by Nichols (2013), which tested Chaudhari (2010) bond wrench against an equivalent unbalanced wrench, Australian bond wrench ASTM 1072 model. A total of eleven prisms were tested in this experiment. On an average American bond wrench results were fifty percent higher as compared to the other tests. It was observed in the Student's t test with 5% acceptance level, that there was no observable statistical distinction in the results obtained for balanced, unbalanced and Australian bond wrench. The results have been illustrated in Table 2.

KINDS OF FLEXURAL FAILURES

Research on masonry bond and compressive strength was conducted with a modified ASTM C1027 bond wrench using different mortars and flexural tests (Sarangapani, Venkatarama Reddy, & Jagadish, 2005). Based on the results obtained, three categories of flexural prism failures were developed. Type 1 is a bond failure indicated by failure of the brick-mortar interface as shown in Figure 10. Type 2 is an intact brick-mortar interface on failure of brick in flexure as shown in Figure 11. Type 3 is a combination of Type 1 and Type 2 failures as shown in Figure 12.

Table 2:

Test results – failure load and peak stress (mpa) Nichols (2013)

Prism/Brick	Test Wrench	Failure L (kg)	Stress (MPa)
1-1	Australian	9.97	0.55
1-2	American	34.53	1.14
2-1	Unbalanced	25.36	0.81
2-2	Failed in setup	0	0
2-3	Failed in setup	0	0
2-4	Balanced	17.45	0.58
3-1	Australian	10.72	0.59
4-1	American	26.42	0.96
4-2	Unbalanced	51.28	1.63
4-3	Balanced	30.73	1.02
5-1	American	52.25	1.53
5-2	Australian	17.09	0.90
5-3	Balanced	17.07	0.57
5-4	Unbalanced	21.00	0.63
6-1	American	57.87	1.65
6-2	Australian	28.65	1.46
6-3	Unbalanced (smooth bond failure)	10.80	0.38
7-1	Balanced	12.58	0.42
7-2	American	75.35	2.03
7-3	Australian	23.12	1.19
8-1	Unbalanced	9.43	0.30
8-2	Balanced	40.71	1.35
8-3	Failed in American Setup	0	0
9-1	American	28.28	1.00
9-2	Australian	21.42	1.11
10-1	Unbalanced	29.25	0.94
10-2	Balanced	31.65	1.05
11-1	American	16.09	0.74
11-2	Australian	6.64	0.39
11-3	Unbalanced	39.14	1.21
11-4	American	41.73	1.30

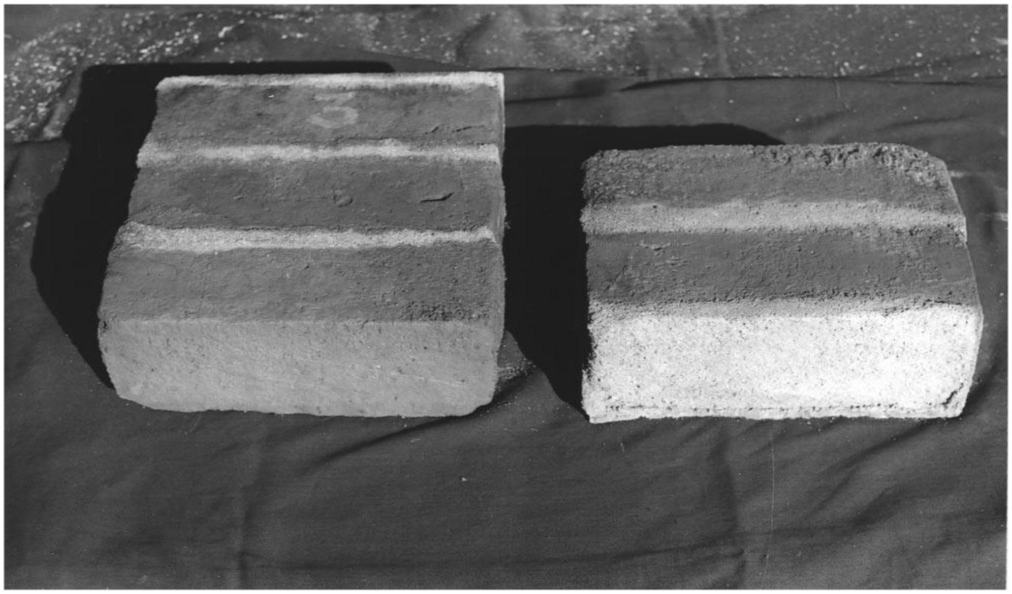


Figure 10: Bond failure at brick-mortar interface (Sarangapani et al., 2005)

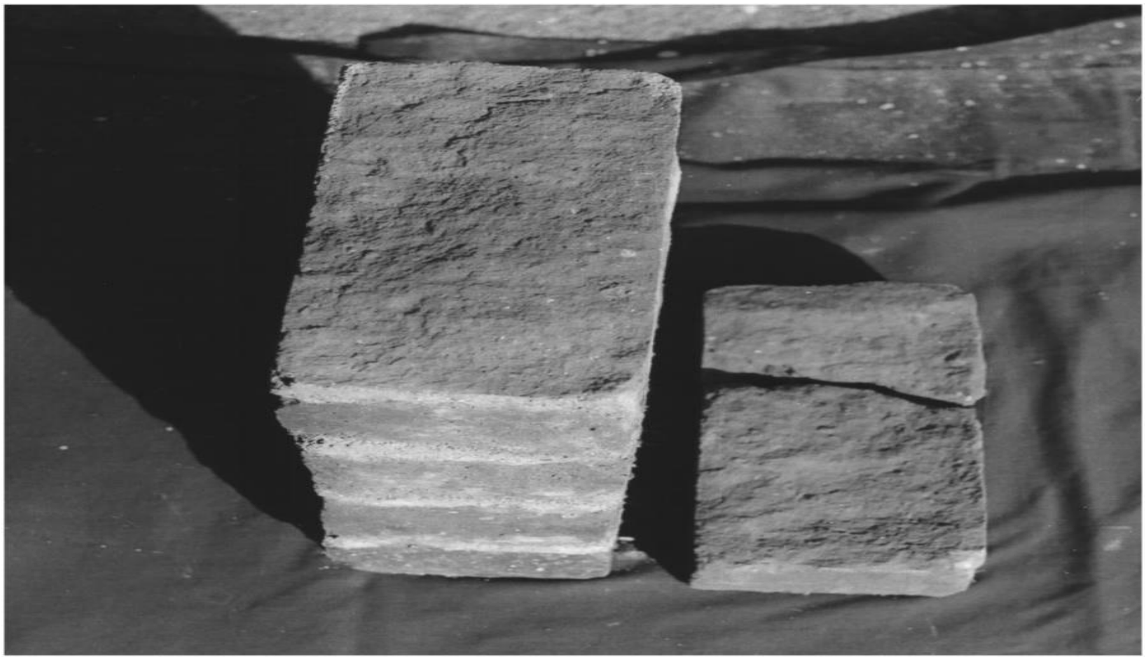


Figure 11: Bond failure when the mortar is still intact (Sarangapani et al., 2005)

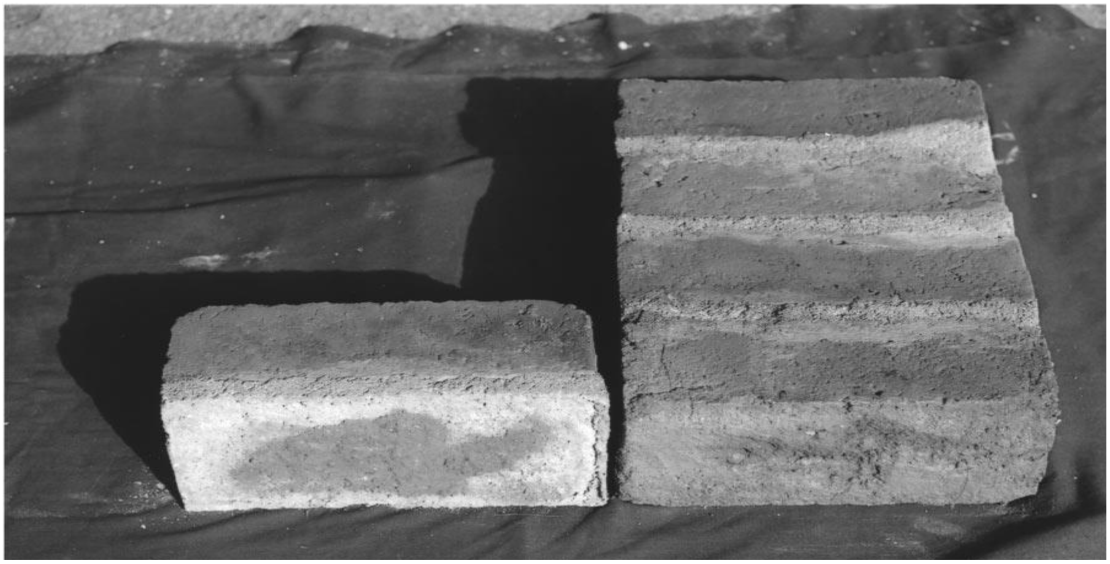


Figure 12: Type 1 and type 2 failures (Sarangapani et al., 2005)

The properties that influence bond strength are initial flow, air content, water retention and workmanship (Boynton & Gutschick, 1964; Edgell, 1987). Workability is not a single property but is a combination of many factors and has the most significant effect on a good bond.

BOND CHARACTERISTICS

In a study conducted on pressed earth blocks and mortar the following results were obtained (Walker, 1999):

1. Close correlation between bond strengths of soil-based mortars and clay content of the mortar mix.
2. Bond failures majorly governed by block strength independent of mortar (but improved with increased water retention in mortars).

3. Significant effect of block moisture content on bond strength during construction (Maximum bond strength is attained at optimum moisture content which is approximately half the blocks' total water absorption value).
4. Higher clay content mortars required higher moisture in block to increase bond strength.
5. Significant decrease in flexural bond strength due to saturation of earth block masonry, with the biggest decrease with soil: cement mortars.

The timeliness of brick setting has a major effect on the bond strength as it reduces on late setting of brick onto the mortar bed (Boynton & Gutschick, 1964; Ritchie & Davison, 1962). Bond strength reduction is proportional to the suction of brick: higher for higher suction brick and lower for low suction brick (Kampf, 1963). Bick realignment after stiffening of brick mortar leads to destruction of the bond (Boynton & Gutschick, 1964). This suggests that the chances brick realignment without damage is greatest for low–suction brick and high water-retention mortar as shown in Figure 13 & Figure 14.

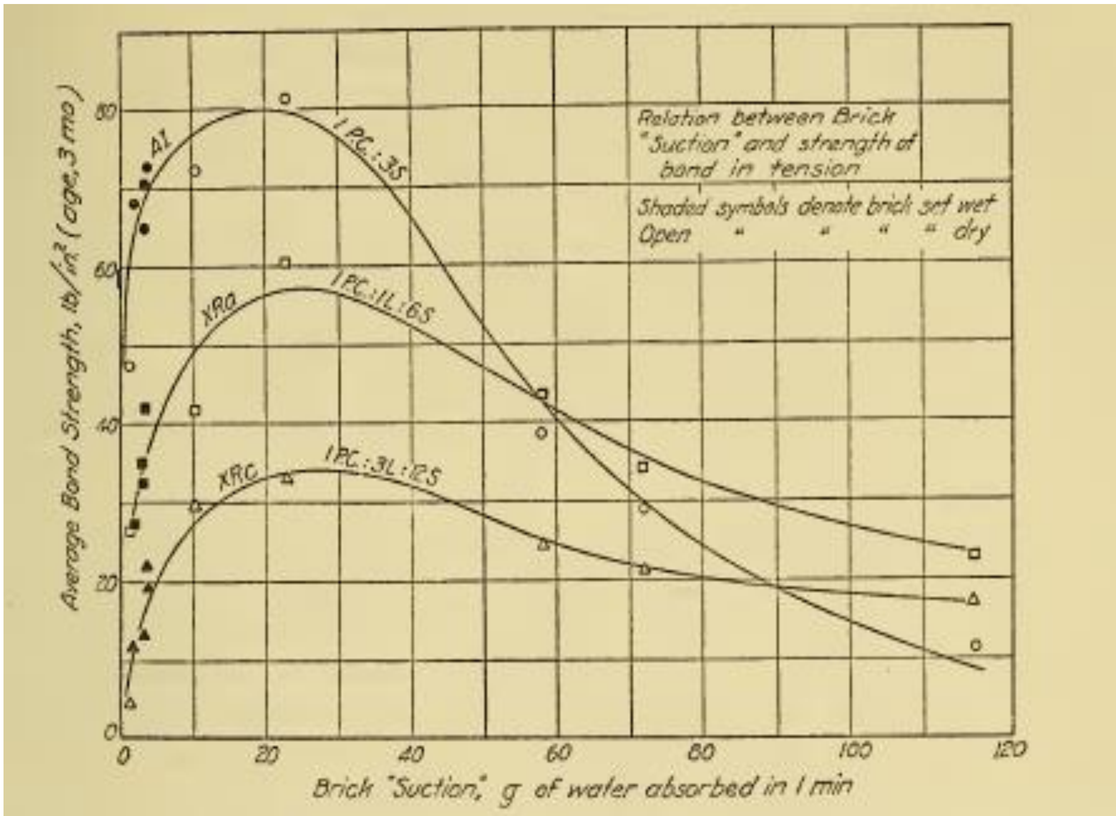


Figure 13: Bond strength results across a range of brick suction values (Boynton & Gutschick, 1964)

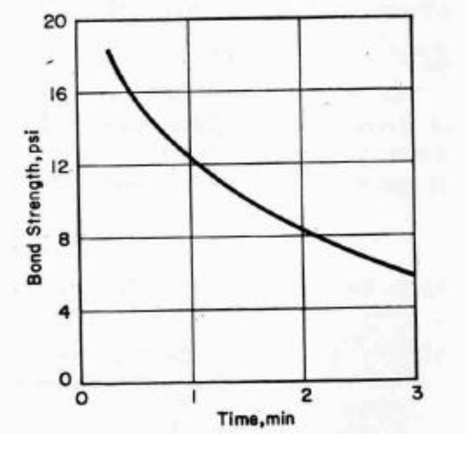


Figure 14: Bond strength plotted against time to placement (Kampf, 1963)

Rao, Reddy, and Jagadish (1996) tested stabilized soil-sand block, stabilized mud brick, and a burnt brick with a variation of mortars. Table 3 shows that there were 5 designations that have particular mortar variations

Table 3:

Mortars used by Venu Madhava Rao, Benkatarama Reddy and Jagadish (1996)

Mortar Designation	Mortar Proportion (by weight)	Water cement ratio	Compressive Strength (MPa) (N=9)	Standard deviation MPa
A	1:4 (cement:sand)	0.9	8.4	0.6
B	1:6 (cement:sand)	1.4	3.6	0.4
C	1:10 (cement:sand)	2.5	0.9	0.1
D	1:1:6 (cement:soil:sand)	1.5	3.8	0.3
E	1:1:10 (cement:lime:sand)	2.5	3.3	0.3

The test results were:

1. Bond strength was found to be higher in the stabilized soil-sand block masonry as compared to stabilized mud block and brick masonry for all types of mortars considered, except for 1:10 cement mortar. There was similar in burnt brick masonry and stabilized soil-sand block masonry in the case of 1:10 cement mortar while stabilized mud block masonry had comparatively lower bond strength.

2. For all types of masonry in the test, combination mortars (soil-cement: D and cement-lime: E) had better bond strengths as compared to 1:6 cement mortars.
3. Bond strengths were approximately the same for 1:1:6 soil-cement mortar and 1:4 cement mortar for all masonry types.
4. The presence of a frog and its magnitude significantly influenced the masonry's flexural bond strength as observed in non-frog surface or the surface with less frog area of the block/brick for all cases, where failure of masonry under flexure was initiated.

The research also included a test demonstrating the effect of moisture content in masonry unit on its flexural bond strength. Burnt brick and stabilized mud block, including mortar proportion type 1:6 (Cement: Sand) and 1:1:6 (Cement: Soil: Sand) were used with 5 variable brick moisture percentages varying between zero and saturation.

The observations made:

1. For all the cases, the flexural strength increases with increase in moisture to a threshold point and drops suddenly.
2. Maximum bond strength is obtained at optimum moisture content. The value of the optimum moisture content is the same for a given type of masonry with varying mortars. Bond strength drops very rapidly beyond the optimum level of moisture content. The values for stabilized mud block masonry and burnt brick masonry are 11% and 13%, respectively.

3. The flexural bond strengths are independent of masonry unit and mortar when masonry unit is saturated.
4. When saturation is not present, the flexural bond strength of stabilized mud block masonry is greater than burnt brick masonry.

Several research studies have been conducted and one of them showed there is a statistically significant bias between the Australian standard bond wrench and ASTM bond wrench (McHargue, 2013). The statistics showed that Australian standard bond wrench has results were 13-16 percent higher than those of ASTM bond wrench. There were variations ranging 20 percent to 40 percent in both the wrenches.

The bond strength calculation has become a keen interest to researchers in recent times (Khalaf, 2005). There are two important concepts, which define the bond between the masonry units and mortar. These are the extent of contact and the stress capable of breaking the contact between mortar and brick (A. Sise, N. Shrive, & E. Jessop, 1988).

This paper aims to provide a statistical comparison of modulus of rupture test results of ASTM E518 Beam Test, which is the standard testing method employed in the United States, as opposed to that of the Australian bond Wrench Test.

Workability, durability, capability to support compressive loads and bond strength to resist flexural stresses are different characteristics of a masonry system (Portland Cement Association, 1994b). A mason aspires workability while the owner aspires durability for less maintenance. But, the engineer is concerned with the capability of the bond to sustain compressive loads and to resist flexural tensile stresses (Portland Cement Association, 1994a). This often leads to a tradeoff between the mason and owner's desires as additional workability is generally achieved at the expense of durability (J. M. Nichols, 2013).

Tensile strength is actually the property of the mortar and masonry unit in combination that expresses their bond strength as opposed to the common assumption of it being the property of the mortar itself (Lawrence, Page, & Scientific, 1994). Masonry is weaker under tensile stresses as compared to compressive stresses due it inherent strength. There are various factors that affect these tensile stresses like masonry type, workmanship, mortar composition and admixtures, which may be a part of the mortar.

In order to study the capability of masonry to resist flexural tensile stresses, a bond wrench is used. There have been efforts made in the past to improve the ways of measuring bond strength. Nichols (2013) investigated the precision and bias of four bond wrenches on a consistent masonry unit. This paper aims at taking these researches further and provides a direct comparison of the standard American wrenches and Australian wrenches under the standard settings achievable in a laboratory to measure the bond strength of a masonry unit.

There have been various works carried out by researchers to investigate bond wrenches and flexural tensile strength characteristics. Varied types of bricks and mortar combinations have been used to study flexural bond strength by researchers all over the world. Initially, it was Baker (Khalaf, 2005) who looked directly at tensile strength of cement mortar. The experiment conducted by Baker was interesting; it failed to test the critical aspect of bond between the mortar and brick.

Various other studies have been conducted by researchers in countries like the

USA (McGinley, 1996), Canada (A Sise et al., 1988), Italy (Luigia Binda, 2008; L Binda, Baronio, Tiraboschi, & Tedeschi, 2003; L Binda, Saisi, & Tiraboschi, 2000) and Australia (Lawrence et al., 1994; J. Nichols, 2000; Page, 1983; Sugo et al., 2000) studied four different bond wrenches through the analysis of their bias results on a consistent masonry unit. Chaudhari (2010) tested the same by a balanced wrench against an unbalanced wrench using their flexural test results.

The strength of the contact between masonry unit and mortar and the stress required to break the mortar are the two important concepts required to be understood in reference to brick and mortar interface (A. Sise, N. G. Shrive, & E. L. Jessop, 1988). The least value among the two determines the flexural strength of each prism couplet.

SUMMARY

Resistance from environmental loads like earthquake and winds require masonry elements to have high tensile flexural strength. Minimum flexural strength, which is typically accepted for an average masonry is 0.1 MPa (J. M. Nichols, 2013). Pre-wetting a pressed brick affects the measured flexural strength and also causes the strength to have a consistent bias (J. Nichols, 2000). The bond strength affects the water integrity of the walls, the masonry endurance and serviceability. Thus, it is important to have a better understanding of such complex property that is vital to masonry design.

CHAPTER III

METHODOLOGY

INTRODUCTION

This chapter outlines the methods used for the research work. The sections of this chapter present the bricks used in the experimental work, the procedure, the preparation of the specimens, equipment setup and the analysis methods.

BRICKS

Figure 15 shows the bricks used in the experimental work.

Figure 15: Bricks used in the experiment

PROCEDURE

The testing procedures involve the AS 3700 Australian standard Bond Wrench Test and the ASTM E518 beam tests. The cement used in the mortar will be ordinary Portland cement and the proportions of this mortar will be one part of lime, one part of Portland cement and 6 parts of sand by volume. Figure 16 shows the prism manufacture. Figure 17 shows some of the completed prisms.

Figure 16: Process of making brick prism

Figure 17: Brick prisms molded out for flexural strength testing

PREPARATION OF THE SPECIMEN

A brick prism has been built with hollow Texas clay bricks, which are stacked vertically. The mortar used between two masonry units will be 10mm. The mortar constituents: cement, lime and sand, will be gathered and purchased. Amount of water that would create adequate workability will be added in the concrete mixer used to make the mortar.

Figure 18 shows some of the manufacture steps.

Figure 18: Lime, sand and cement gathered together and measured before being added to the concrete mixer

Figure 19 shows the mortar at mixing. Figure 20 shows the mortar mixer. Figure 21 shows the main frame for the bond wrench testing.

Figure 19: 1:1:6 cement: lime: water mortar mix

Figure 20: The concrete mixer user to prepare mortar for the experiment

Figure 21: Main frame of the bond wrench

EQUIPMENT SETUP

All bond wrenches are set up the same way. In order to vertically adjust the masonry specimen according to the lower hydraulic clamping bracket, a hydraulic lift table is placed in the center of the mainframe base system, and a jack is used, Figure 22. Figure 23 shows the device used to determine the force to break the prism.

Figure 22: Hydraulic jacks used to lift the specimen in the experiment

Figure 23: Measurement of the weight needed to break a bond

The masonry specimen is placed tightly during testing and adjusts horizontally with the help of a horizontal piston. The loading arm attached to the upper clamping bracket has a bucket hooked to it. Figure 24 shows the final arrangement.

Figure 24: The experiment setup with the bond wrench and prism ready for loading through addition of loads in the bucket.

Figure 25 shows the Australian standard bond wrench.

Figure 25: AS3700 bond wrench

Figure 26 shows the setup for the beam tests.

Figure 26: E518 test setup

BIAS ISSUES

During the construction of all prisms, the prism construction parameters are kept the same to negate potential variability in testing results. Australian bond wrench had a total of 125 tests while the ASTM E518 had 25 tests.

PROCEDURE FOR EQUIPMENT: AS 3700 BOND WRENCH

The experimental procedure is:

1. In the retaining frame, the specimen’s lower portion is retained securely. If necessary counterbalancing weights are added to the retaining frame, which when fully loaded ensures the whole apparatus’s stability.
2. The prism is clamped to the bond wrench such that the arm is maintained at a horizontal position.
3. Calculate:

- Mass of the container with the contents (P), within the range of -100 to 100g
- Mass of the loading arm (Pl), to within the range of -100 to 100g
- Distance between center of prism and centroid of loading arm (Ll)
- Distance between prism’s prism and point of loading (L)
- Width of cross-section area of mortar-bedded area measured perpendicular to the loading arm (b)
- Depth of cross-section area of mortar-bedded area measured parallel to the loading arm (d)

The flexural strength of each test joint of the specimen shall be:

$$Fg = ((6\,(PL + PlLl) / bd^2)) - ((P + P1)/bd)$$

where,

- ***Fg*** is the gross area flexural tensile strength, MPa
- ***Ll*** is the distance between center of prism and centroid of loading arm, mm
- ***Pl*** is the loading arm’s weight, N
- ***L*** is the distance between center of prism and loading point, mm
- ***b*** is the mortar-bedded area’s cross-sectional width perpendicular to the loading arm of the upper clamping bracket, mm
- ***P*** is the maximum applied load, N
- ***d*** is the weight of loading arm, N

A sample size of 25 prisms will be tested with the AS 3700 unbalanced bond wrench.

PROCEDURE FOR EQUIPMENT: ASTM E518 BEAM TEST

The experimental procedure is as follows:

1. The prism should be turned to its side according to its molded position and centered on the support blocks. The loading system centered in relation to the applied force.
2. The load-applying blocks should be brought in contact with the specimen’s surface at the third points and a load of 3-6% of the estimated ultimate load is to be applied.

3. Load the prism continuously at a constant rate to the breaking point without any shock.

The flexural strength of each of the specimen is calculated by:

$R = PL/(bd^2)$

where,

- **L** is the span length
- **R** is the flexural strength, MPa
- **b** is the average width of specimen, mm
- **P** is the maximum applied load displayed by the testing machine
- **d** is the average depth of specimen, mm

The ASTM E518 beam testing will test a sample size of 25 prisms.

CHAPTER IV

RESULTS

INTRODUCTION

A summary of the results of the experiment carried out for this research has been presented. An outline of the flexural strengths and the results has been illustrated in the following tables. This chapter summarizes the brick measurements, flexural strength

BRICK MEASUREMENTS

Table 4 shows the brick measurements. The average length of the brick is noted as 194 mm, width is 57.2 mm and an area of 10093 mm^2.

FLEXURAL STRENGTH

Calculation of the flexural strength is done based on the self-weight of the wrench (m_1), self -weight of the brick (m_3) and the failure load (m_2), the distance between inside edge of tension gripping block and the center of gravity (d_1) in mm, the distance between the edge of the tension gripping block and the loading handle, in mm (d_2), the masonry unit width (t_u). The mass (m_3) of the brick is 1.76 kg's. The design analysis is:

- One member's design Cross-sectional area (A_d) in mm^2 = 11089.74 mm^2
- Beam's fractured section modulus = 80633.71mm^3

$(Z_d) = (bh^2/6)$, in cubic millimeters

Total compressive force exhibited on the tested joint's bedded area (Fsp), in Newton = 9.81 ($m_1 + m_2 + m_3$)

Bending moment about the centroid at failure for the test joint's bedded area (M_{sp}), in Newton millimeters = $9.81m_2 (d_2 - t_u / 2) + 9.81m_1(d_1 - t_u / 2)$

Table 5 shows the measurements of the bond wrenches for the analysis.

Table 4:

Brick measurements

Length	Width	Area
194.2	57.43	11152.91
193.6	57.2	11073.92
194.4	57.32	11143.01
193.2	56.8	10973.76
194.9	57.46	11198.95
194.1	57.1	11083.11
194.5	56.45	10979.53
193.1	57.8	11161.18
194.6	57.71	11230.37
194.3	56.78	11032.35

Note: All dimensions in mm

Table 5:

Measurements of the bond wrench

Variable	Australian Standard
d_1	114.3
d_2	708.4
m_1	4.7

Note: Lengths in millimeter and Weight in kilograms

Flexural Strength of the bond wrench (f_{sp}), in MPa

$= (M_{sp} / Z_d) - (F_{sp} / A_d)$

The measurements were taken during the experiments and recorded into tables. The respective values were calculated using the formulas discussed before. The following are the tables consisting of the observed results:

- Table 6 shows the results for the first twenty samples.
- Table 7 shows the results for another eighteen samples for the balanced bond wrench.
- Table 8, Table 9, Table 10, Table 11 & Table 12 shows the stress values for the rest of samples tested by Australian Standard bond wrench.

Table 6:

Flexural strength of samples 1-1 to 4-5 using Australian Standard Bond Wrench

No	m_2	F_{sp}	M_{sp}	f_{sp}
1-1	20.92	268.5978	143468.5	1.755042
1-2	12.42	185.2128	86781.7	1.059545
1-3	22.09	280.0755	151271.3	1.850775
1-4	18.31	242.9937	126062.3	1.541483
1-5	15.48	215.2314	107188.9	1.309923
2-1	13.72	197.9658	95451.44	1.165915
2-2	9.46	156.1752	67041.36	0.817348
2-3	6.82	130.2768	49435.11	0.601335
2-4	4.3	105.5556	32629.14	0.39514
2-5	12.94	190.314	90249.59	1.102093
3-1	11.02	171.4788	77445.05	0.944992
3-2	14.2	202.6746	98652.58	1.20519
3-3	6.16	123.8022	45033.54	0.547332
3-4	6.64	128.511	48234.68	0.586607
3-5	8.08	142.6374	57838.09	0.704432
4-1	11.14	172.656	78245.33	0.954811
4-2	10.3	164.4156	72643.34	0.886079
4-3	Failed	0	0	0
4-4	13.48	195.6114	93850.87	1.146277
4-5	8.74	149.112	62239.65	0.758435

Table 7:

Flexural strength of samples 5-1 to 8-3 Australian Standard Bond Wrench

No	m_2	F_{sp}	M_{sp}	f_{sp}
5-1	11.92	180.3078	83447.18	1.018633
5-2	9.46	156.1752	67041.36	0.817348
5-3	15.58	216.2124	107855.8	1.318106
5-4	14.2	202.6746	98652.58	1.20519
5-5	7.36	135.5742	53036.38	0.645519
6-1	10.54	166.77	74243.91	0.905717
6-2	6.76	129.6882	49034.96	0.596425
6-3	5.86	120.8592	43032.83	0.522785
6-4	15.58	216.2124	107855.8	1.318106
6-5	Failed	0	0	0
7-1	5.26	114.9732	39031.41	0.473691
7-2	8.92	150.8778	63440.08	0.773164
7-3	7.78	139.6944	55837.38	0.679885
7-4	8.38	145.5804	59838.8	0.728979
7-5	12.34	184.428	86248.17	1.052999
8-1	4.36	106.1442	33029.28	0.40005
8-2	4.48	107.3214	33829.57	0.409869
8-3	8.5	146.7576	60639.08	0.738798

Table 8:

Flexural strength of samples 8-4 to 12-3 using Australian Standard Bond Wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
8-4	7.24	134.397	52236.1	0.635701
8-5	9.7	158.5296	68641.92	0.836986
9-1	15.64	216.801	108256	1.323015
9-2	5.68	119.0934	41832.41	0.508056
9-3	14.68	207.3834	101853.7	1.244465
9-4	Failed	0	0	0
9-5	6.7	129.0996	48634.82	0.591516
10-1	6.4	126.1566	46634.11	0.566969
10-2	13.96	200.3202	97052.01	1.185552
10-3	6.4	126.1566	46634.11	0.566969
10-4	6.76	129.6882	49034.96	0.596425
10-5	13.24	193.257	92250.3	1.12664
11-1	14.8	208.5606	102654	1.254284
11-2	10.96	170.8902	77044.91	0.940083
11-3	Failed	0	0	0
11-4	11.74	178.542	82246.75	1.003905
11-5	6.58	127.9224	47834.54	0.581697
12-1	5.2	114.3846	38631.27	0.468781

Table 9:

Flexural strength of the samples 12-2 to 15-4 Australian Standard Bond Wrench

S No	M_2	F_{sp}	M_{sp}	f_{sp}
12-2	12.58	186.7824	87848.74	1.072636
12-3	11.26	173.8332	79045.62	0.96463
12-4	6.58	127.9224	47834.54	0.581697
12-5	15.28	213.2694	105855.1	1.293559
13-1	10.72	168.5358	75444.34	0.920445
13-2	9.4	155.5866	66641.21	0.812439
13-3	15.52	215.6238	107455.7	1.313196
13-4	5.2	114.3846	38631.27	0.468781
13-5	Failed	0	0	0
14-1	13.48	195.6114	93850.87	1.146277
14-2	8.86	150.2892	63039.94	0.768254
14-3	4.9	111.4416	36630.56	0.444234
14-4	5.74	119.682	42232.55	0.512966
14-5	9.82	159.7068	69442.21	0.846804
15-1	6.58	127.9224	47834.54	0.581697
15-2	4.42	106.7328	33429.42	0.404959
15-3	13.06	191.4912	91049.88	1.111911
15-4	5.44	116.739	40231.84	0.488419

Table 10:

Flexural strength of samples 15-5 to 19-2 using Australian Standard Bond Wrench

S No	m2	Fsp	Msp	f_{sp}
15-5	10.78	169.1244	75844.48	0.925355
16-1	8.26	144.4032	59038.51	0.71916
16-2	10	161.4726	70642.63	0.861533
16-3	14.68	207.3834	101853.7	1.244465
16-4	Failed	0	0	0
16-5	11.44	175.599	80246.04	0.979358
17-1	5.5	117.3276	40631.98	0.493328
17-2	11.74	178.542	82246.75	1.003905
17-3	12.1	182.0736	84647.61	1.033361
17-4	11.5	176.1876	80646.19	0.984267
17-5	Failed	0	0	0
18-1	14.2	202.6746	98652.58	1.20519
18-2	6.34	125.568	46233.97	0.56206
18-3	9.76	159.1182	69042.07	0.841895
18-4	15.52	215.6238	107455.7	1.313196
18-5	9.46	156.1752	67041.36	0.817348
19-1	15.04	210.915	104254.6	1.273921
19-2	11.2	173.2446	78645.48	0.95972

Table 11:

Flexural strength of samples 19-3 to 22-5 using Australian Standard Bond Wrench

S No	m2	Fsp	Msp	f_{sp}
19-3	11.68	177.9534	81846.61	0.998995
19-4	10.72	168.5358	75444.34	0.920445
19-5	15.64	216.801	108256	1.323015
20-1	13.66	197.3772	95051.3	1.161005
20-2	4.9	111.4416	36630.56	0.444234
20-3	7.72	139.1058	55437.24	0.674976
20-4	5.68	119.0934	41832.41	0.508056
20-5	14.14	202.086	98252.44	1.20028
21-1	16	220.3326	110656.8	1.352472
21-2	12.58	186.7824	87848.74	1.072636
21-3	4.96	112.0302	37030.7	0.449144
21-4	11.26	173.8332	79045.62	0.96463
21-5	11.68	177.9534	81846.61	0.998995
22-1	8.26	144.4032	59038.51	0.71916
22-2	9.1	152.6436	64640.5	0.787892
22-3	Failed	0	0	0
22-4	9.28	154.4094	65840.93	0.80262
22-5	4.78	110.2644	35830.28	0.434416

Table 12:

Flexural strength of samples 23-1 to 25-5 using Australian Standard Bond Wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
23-1	9.22	153.8208	65440.79	0.79771
23-2	11.38	175.0104	79845.9	0.974448
23-3	11.74	178.542	82246.75	1.003905
23-4	6.16	123.8022	45033.54	0.547332
23-5	15.22	212.6808	105455	1.288649
24-1	14.98	210.3264	103854.4	1.269012
24-2	8.8	149.7006	62639.79	0.763345
24-3	5.08	113.2074	37830.99	0.458963
24-4	8.38	145.5804	59838.8	0.728979
24-5	11.26	173.8332	79045.62	0.96463
25-1	11.5	176.1876	80646.19	0.984267
25-2	13.54	196.2	94251.02	1.151187
25-3	9.82	159.7068	69442.21	0.846804
25-4	6.46	126.7452	47034.25	0.571879
25-5	12.82	189.1368	89449.31	1.092274

Table 13 shows the results for specimens tested using ASTM E518 beam test method

Table 13:

Flexural strength of samples 1-23 using ASTM E518 beam test

S No	Load	Stress Value
1	26.56	0.533856
2	22.65	0.455265
3	50.34	1.011834
4	12.74	0.256074
5	39.45	0.792945
6	22.23	0.446823
7	25.65	0.515565
8	24.11	0.484611
9	20.96	0.421296
10	18.23	0.366423
11	26.24	0.527424
12	28.33	0.569433
13	30.32	0.609432
14	53.25	1.070325
15	27.43	0.551343
16	26.23	0.527223
17	24.65	0.495465
18	22.84	0.459084
19	23.45	0.471345
20	28.88	0.580488
21	29.11	0.585111
22	32.85	0.660285

Table 14:

Flexural strength of samples 23-25 using ASTM E518 beam test

S No	Load	Stress Value
23	13.85	0.278385
24	52.84	1.062084
25	28.23	0.567423

Table 15 shows the results for the initial rate of absorption of 10 samples.

Table 15:

Initial rate of absorption for bricks (10 samples)

S No	Water absorbed(grams)	IRA(kg/m^2/min)
1	20.34	0.917064
2	17.73	0.799388
3	14.39	0.648798
4	18.53	0.835457
5	20.23	0.912104
6	19.27	0.868821
7	15.75	0.710116
8	21.13	0.952682
9	16.49	0.74348
10	17.14	0.772786

The Initial rate of absorption was calculated for the bricks used in the experiment as shown in Table 15. The average rate of absorption was 0.82 kg/m^2/min. The value lies between the acceptable ASTM C67 standard limits of 0.5 to 1.5 kg/m^2/min. Figure 27 shows the IRA test setup.

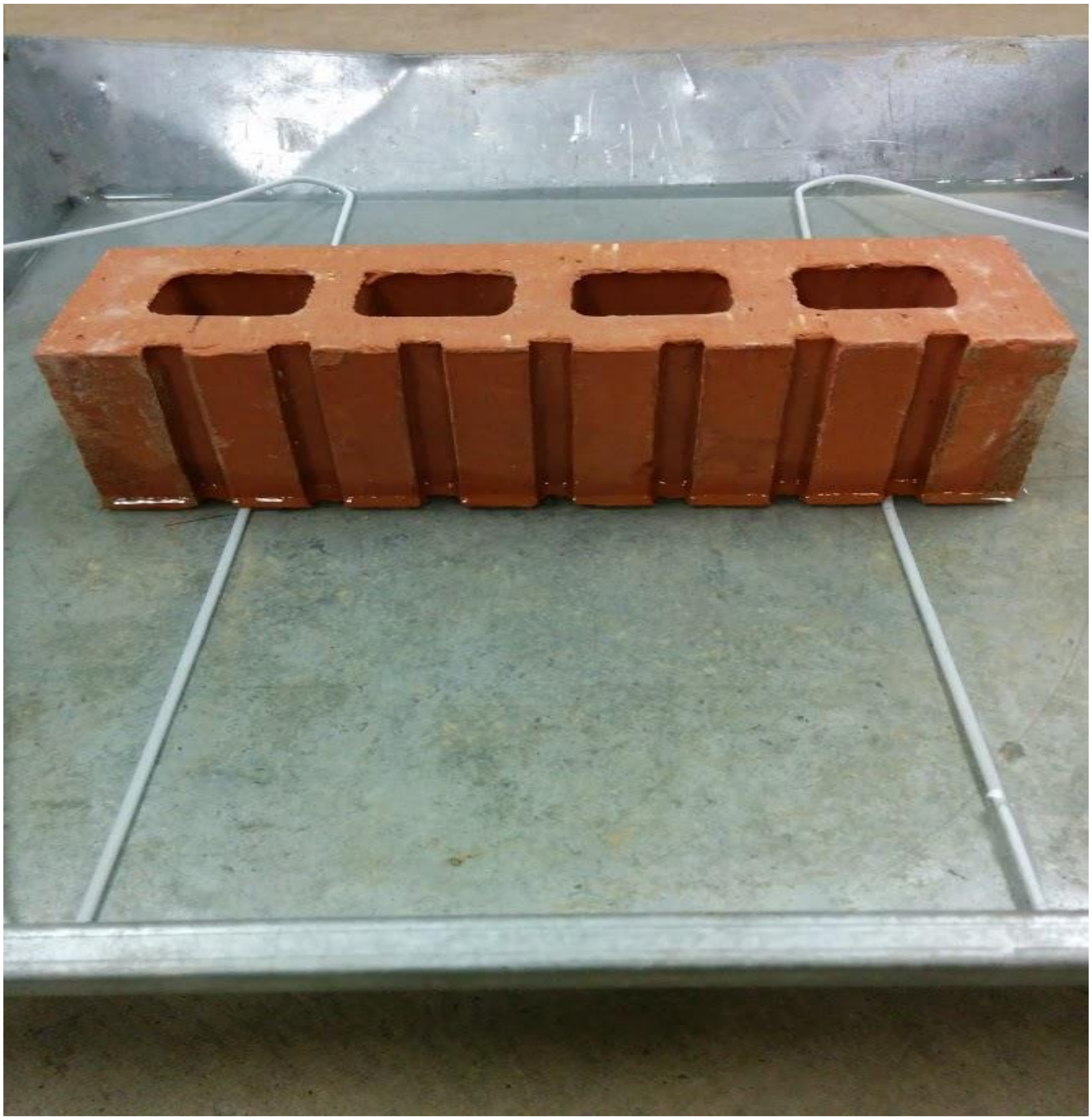


Figure 27: Absorption test on sample brick

A Student t Test analysis has been carried out between Australian Standard bond wrench and ASTM E518 beam test, Table 16 shows the method for interpreting Student's t Test carried out on two samples.

Table 16:

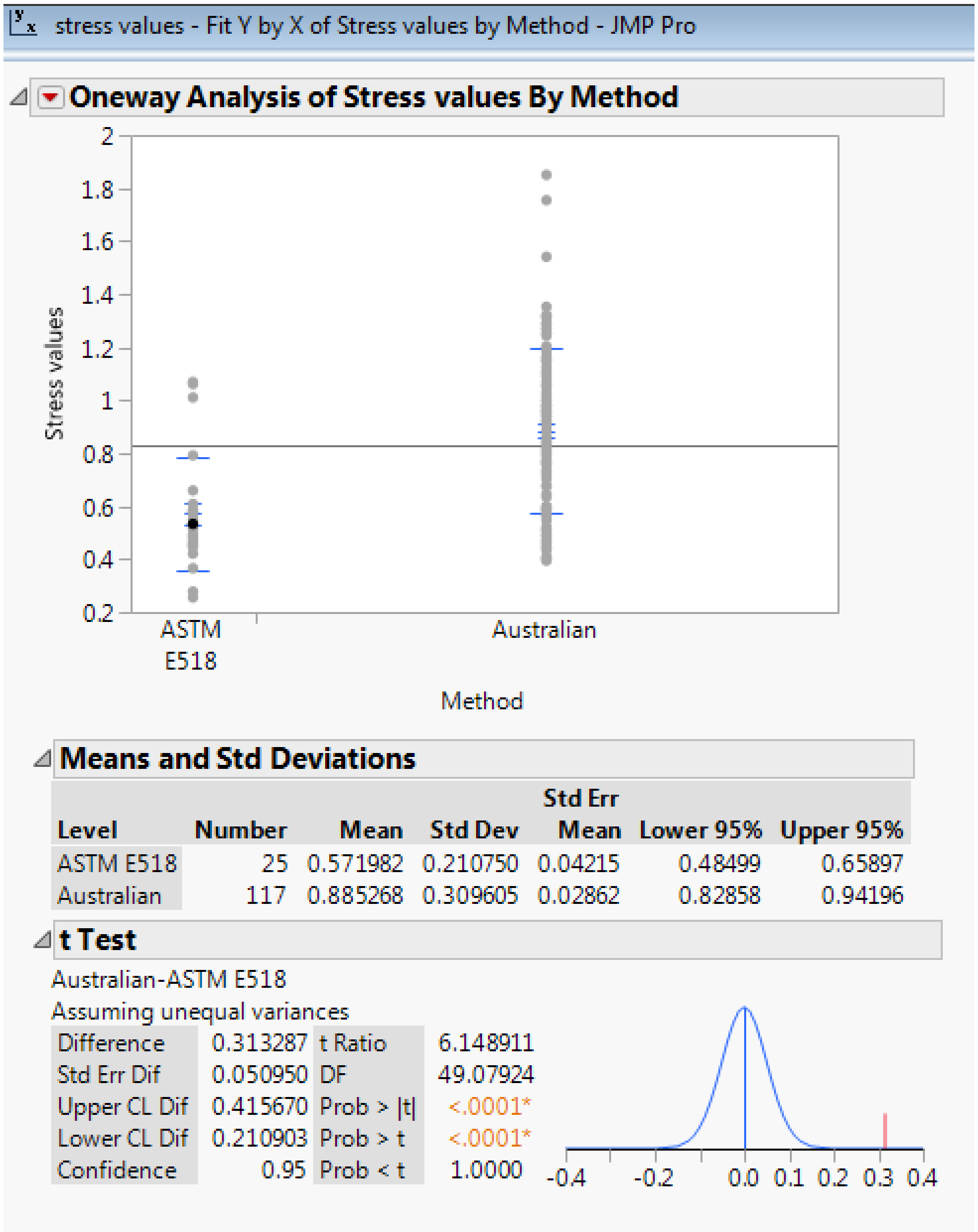
Interpretation of student t-test

Observation	Conclusion
Test statistic > critical value ($t > t_{crit}$)	Reject null hypothesis
test statistic < critical value ($t < t_{crit}$)	Accept null hypothesis
p value > α	Accept null hypothesis
p value < α	Reject null hypothesis

The null hypothesis illustrates there exists no bias between the flexural strength values from the Australian Standard bond wrench and ASTM E518 beam test. The present test is a two sided test, and hence two tail values have been used for the analysis.

If t test comparisons between the sample sets result in (t statistic > t critical) and (p value < α), we can reject the null hypothesis that the means are the same.

Figure 28 shows the results of the statistical analysis comparison.



Oneway Analysis of Stress values By Method

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
ASTM E518	25	0.571982	0.210750	0.04215	0.48499	0.65897
Australian	117	0.885268	0.309605	0.02862	0.82858	0.94196

t Test

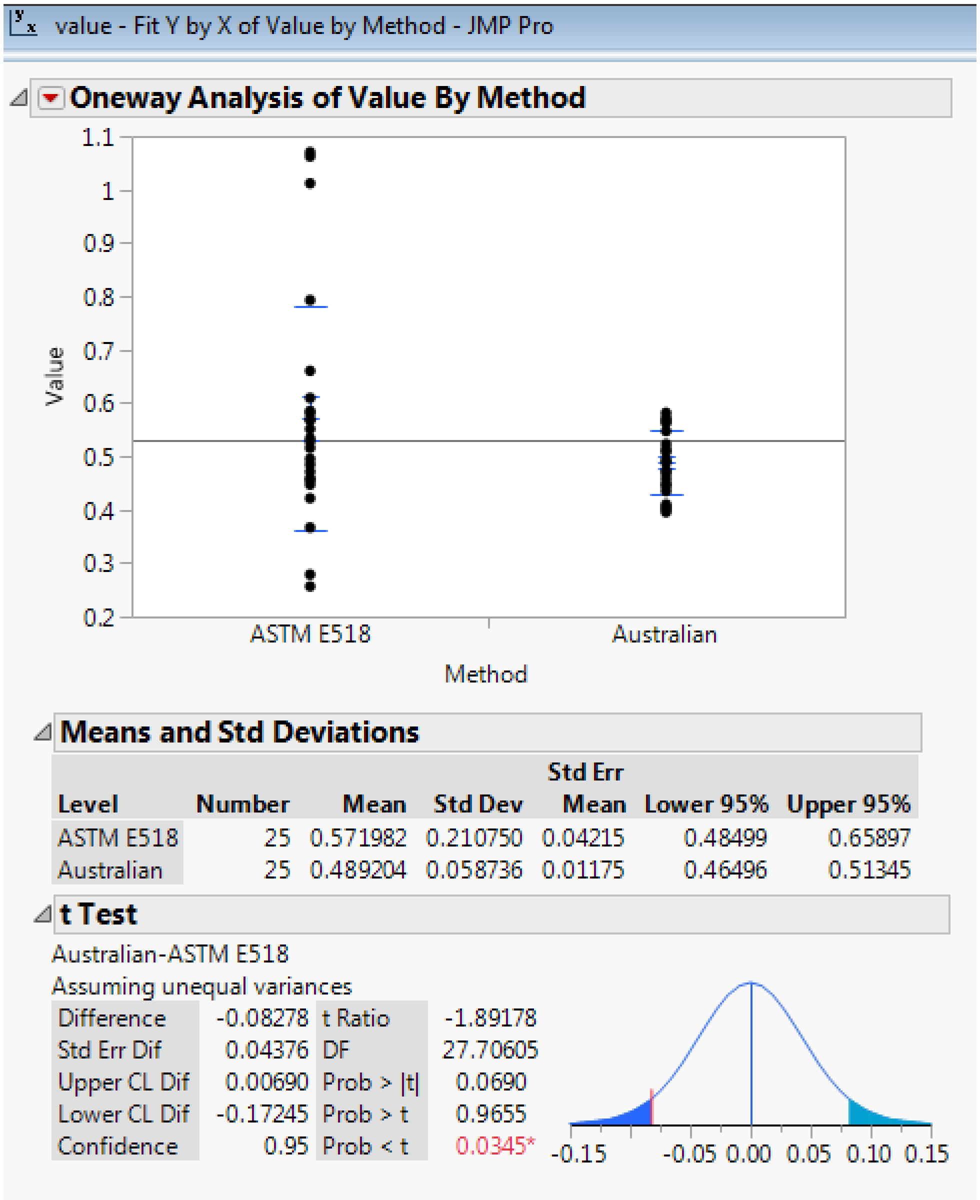
Australian-ASTM E518

Assuming unequal variances

Difference	0.313287	t Ratio	6.148911
Std Err Dif	0.050950	DF	49.07924
Upper CL Dif	0.415670	Prob > |t|	<.0001*
Lower CL Dif	0.210903	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

Figure 28: Student t test- Australian Standard bond wrench – ASTM E518 comparison

Figure 29 shows a Student’s t Test analysis of the weakest joint in each AS Standard Wrench tests and the E518 test.



Oneway Analysis of Value By Method

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
ASTM E518	25	0.571982	0.210750	0.04215	0.48499	0.65897
Australian	25	0.489204	0.058736	0.01175	0.46496	0.51345

t Test

Australian-ASTM E518

Assuming unequal variances

Difference	-0.08278	t Ratio	-1.89178
Std Err Dif	0.04376	DF	27.70605
Upper CL Dif	0.00690	Prob > |t|	0.0690
Lower CL Dif	-0.17245	Prob > t	0.9655
Confidence	0.95	Prob < t	0.0345*

Figure 29: Student t test- Comparison of weakest joint of ASTM E518 & Australian bond wrench

SUMMARY OF RESULTS

From the above t test analysis the mean of the values from Australian bond wrench is 0.885 MPa and the mean of the values from ASTM E518 beam test is 0.571MPa.

From the above t test analysis (see Figure 28), it can be observed that the mean values of the Australian bond wrench and ASTM E518 beam test are dissimilar. The stress values for joints, which failed were not considered for the statistical analysis; their values were zero and they were outliers for the given data sample.

The initial rate of absorption for brick samples was calculated and the average value was 0.82 $kg/m^2/min$ which is under acceptable ASTM C67 limits.

A normal distribution was observed for both the data set obtained from Australian bond wrench experiment and ASTM E518 beam test and thus the t-test was valid. The values obtained from ASTM E518 method are obtained from the joint which is weakest and hence the mean is lower (0.571 MPa) than the values obtained from Australian bond wrench. Since the Australian bond wrench measures the strength for each joint, the mean value is on the higher side (0.885 MPa). The null hypothesis is rejected because the probability of alternative being true is 99.99% at 95% confidence interval, this shows evidence that there exists a bias between Australian standard bond wrench and ASTM E518 beam test.

The student t-test (see Figure 29) conducted between the lowest stress values obtained from Australian Standard bond wrench and ASTM E518 beam method shows that null hypothesis can’t be rejected. This means that there is no bias when the stress values of weakest joints tested by Australian Standard bond wrench are compared with the joints tested by ASTM E518 beam test.

CHAPTER V

CONCLUSIONS

Flexural bond strength which is measured using a bond wrench is a significant factor that governs the joint performance under different loading conditions. There have been different bond wrenches developed throughout the years in past. The first was developed in an Australian laboratory and this method has been studied since that time.

In the 1980's, an Australian bond wrench was developed and the later an ASTM C 1072 bond wrench was developed. Both these wrenches are unbalanced hence they impart a torque to the prism on placement. A TAMU unbalanced and balanced bond wrench were developed by two graduate students in TAMU. These bond wrenches consist of variation with respect to the upper clamping buckets.

In total four bond wrenches have been developed in TAMU namely Australian, American, TAMU balanced and unbalanced. Various studies have been conducted at TAMU to analyze the bias between the different wrenches in terms of mean flexural strength with a set of experimental masonry joints. These studies lead to the conclusion that there is no unacceptable bias existed in the flexural strength values obtained using TAMU balanced and unbalanced wrench. Researchers have also found that there exists a bias between American Bond wrench and Australian Bond wrench.

This research study uses Portland cement and aims to compare the flexural strength values obtained by the Australian bond wrench and ASTM E518 bond wrench in order to check for a bias between them. For this purpose, a total of 50 prisms were built which were tested in the same weather conditions.

Each prism consisted of 6 bricks with 5 joints and the mortar used was 1:1:6 with Portland cement. The first set of 25 prisms was used with Australian bond wrench and the second set of 25 prisms was used with ASTM E518 bond wrench. The values obtained through these tests were analyzed using student's t-test analysis. The plots obtained infer that the mean flexural strength values of Australian bond wrench were higher than ASTM E518 bond wrench mean flexural strength values. The plots obtained were quite dissimilar.

We can conclude that the values obtained using ASTM E518 were low because of failure in weakest joint in the prism. The Australian bond wrench measures each joint in the prism. The stress values obtained in this test are according that particular joint. The ease of the setup of apparatus for testing the bond strength according to flexural analysis of joints and the weight of the instrument makes it more favorable to use.

Further research can be conducted with the use of Texan red brick. Other bond wrenches can be compared with the discussed bond wrenches to analyze the presence of bias between them.

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