FLEXURAL STRENGTH OF WATER-SATURATED CLAY BRICK PRISMS

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ABSTRACT

This research aimed to understand the behaviour of water-saturated masonry when subject to flexure. It is known that when masonry is saturated, it loses some of its compressive strength; however, a review of the relevant literature did not confirm that this is true for flexure. This study required a testing apparatus called a "bond wrench" and six- brick masonry prisms to be built to test flexural strength in saturated and ambient laboratory conditions. The bond wrench, built at Gonzaga University in consultation with local industries for welding procedures, consists of a frame, a pressure device, and an analog gauge. Each joint in a prism was tested for failure in flexure by adjusting the bond wrench apparatus; therefore, five data points were obtained from each prism. A professional mason with 40 years of experience constructed all 40 prisms used for testing. Twenty of these prisms were built using Type N mortar and the other twenty with Type S mortar; two of the most commonly used mortars in building construction. The prisms were cured in the laboratory and tested at 14 days and 28 days of curing. Half of the prisms were submerged in water two days prior to testing to ensure complete saturation. The remaining prisms were tested dry and the results were compared. The research can be employed to better understand masonry construction subject to flexure in extremely wet environments and in submerged conditions.

KEYWORDS: brick masonry, saturation, flexural strength, prisms, bond wrench

INTRODUCTION

Clay brick masonry is one of the world's oldest and most widely used construction materials. In common construction applications, like walls, the structures must be able to resist both axial loading and lateral loading. The flexural strength, or the ability of structures to resist these lateral loadings, depends upon the strength of the bond at the mortar-masonry interface [1]. Previous studies of mortar and masonry units have reported a wide range of flexural strength values [2-5]. Because the flexural strength is often less than the compressive strength [1], understanding how environmental conditions influence the flexural strength is of critical importance.

A review by Wood showed that there has been extensive research into the flexural strength of clay brick masonry dating back to the 1980's [6]. Factors shown to influence flexural strength include: mortar composition [3, 7], construction quality [6], curing conditions [8], and mortar joint geometry and thickness [8]. These factors indicate that the flexural strength is not only dependent upon the material properties of the mortar and masonry, but also the combined masonry-mortar unit.

Development of the masonry-mortar bond was first explained by Lawrence and Cao [9]. Their work showed that the bond is created via the formation of cement hydration products on the brick surface and inside the brick pores. Masonry-mortar unit properties such as the initial rate of absorption [10, 11] have been shown to influence the extent of bond formation and it has been hypothesized that the physical pore structure and surface texture may also impact the formation of bonding cement hydration products [10].

One area where research was inadequate was the influence of water permeance. Studies have found that mortars with high water retention capabilities have increased flexural strength because of the increased ability for the mortar to flow into voids along the mortar-masonry interface. An investigation by Drysdale and Gazzola found that concrete brick prisms constructed and cured in ambient laboratory conditions had higher flexural strengths than those prisms built in high-humidity conditions (70% to 80 % RH) [4]. While this research suggests that the compressive strength of clay brick masonry units should decrease after being completely saturated, there are no studies that indicated a similar decrease in flexural strength.

The purpose of this research was to investigate the influence of water saturation on the flexural strength of clay brick masonry structures. Six-brick prisms were constructed and tested in accordance with American Society for Testing and Materials (ASTM) Standard C1072 [12] using Type N and Type S mortars. Based on previous research [3], the prisms constructed with Type S mortar display a greater flexural strength than those constructed with Type N mortar. Flexural strength of unsaturated and water saturated prisms was determined at 14 and 28 days post-construction. Results from this research indicate the need for improved testing methodologies and additional research into the effects of water saturation.

MATERIALS AND METHODS

Flexural bond strength was measured using the procedure described in ASTM Standard C1072-06 unless otherwise noted. In summary, the method uses a bond wrench (Figure 1) to place a chosen mortar joint in flexure.

Figure 1: The Bond Wrench Was Constructed by the Gonzaga University Machine Shop in Accordance with ASTM C1072.

A single batch of extruded 9.2 x 19.4 x 5.7 cm (3-5/8 x 7-5/8 x 2-1/4 in) clay bricks (Mutual Materials) with three 3.8 cm (1-1/2 in) diameter cores was used to construct test prisms (Figure 2). The section properties of the brick face can be found in Table 1.

Table 1: Section Properties of the Net Bedded Area of the Bricks

Net Bed Area	Moment of Inertia	Section Modulus
mm^2 (in^2)	mm^4 (in^4)	mm^3 (in^3)
4152 (6.43)	20776712 (49.92)	451300 (27.54)

This standard brick size is used in residential and commercial construction. Prisms were constructed using two mortar types: Type S and Type N. Type S mortar has a higher cement to total volume ratio and is employed in above ground exterior and interior use as it is better able to withstand weather exposure. Type N mortar has a lower cement ratio in its composition and is used in above and below ground construction. The water to cement ratio and gradation of the fill material were kept constant for all tests.

Figure 2: Construction of the Masonry Prisms.

A professional mason was hired to construct the prisms. The research team relied on the mason's expertise in lieu the ASTM C1072 [9] required slump and moisture content tests. The mason constructed 40 prisms comprised of 6 bricks with 5 mortar joints aligned in a "stack bond" fashion. Twenty of the prisms were constructed with Type S mortar (total: 100 mortar joints) and 20 prisms were constructed with Type N mortar. Prisms were cured in the laboratory until testing. After 12 days of curing, five Type S prisms and five Type N prisms were fully submerged in room temperature water. The prisms were soaked for 48 hours before testing to achieve maximum saturation. Five unsaturated Type S prisms and five unsaturated Type N prisms were simultaneously tested for comparison. This process was repeated with the remaining prisms beginning after 26 days of curing. For each flexural strength test, (Figure3), the maximum pressure prior to failure and the mortar failure mode were recorded.

Figure 3: Prism Inserted in the Bond Wrench Prior to Testing.

Testing deviated from the ASTM standard by use of a manually operated hydraulic jack that could not apply a constant force as slowly as required by the standard. The 14 day tests were also performed without a bearing plate between the clamping screws and the clay brick.

The tensile flexural bond strength of each prism was calculated using Equation 1 in accordance with ASTM C1072:

$$F_n = \frac{R*A_s*L+P_1*L_1}{S} - \frac{R*A_s+P_1}{A_n} \quad (1)$$

Where:
F_n = net area flexural tensile strength, psi,
R = highest recorded pressure before failure, psi,
A_s = area of the hydraulic jack head, in^2,
L = distance from the point of load to the center of the prism, in,
S = section modulus of net bedded area of the prism (I/c), in^3,
L_1 = distance from the centroid of the lever arm to the center of the prism, in,
A_n = net area of the mortar face, in^2.

The net area of the mortar face and the section modulus were calculated from equations 2 and 3, respectively.

$$A_n = 2b * t_{fs} \quad (2)$$

$$I = \frac{b*(t_{fs})^3}{6} + \frac{b*t_{fs}*\left(d-t_{fs}\right)^2}{2} \quad (3)$$

Where:
b = cross sectional width of the mortar bedded area, perpendicular to the loading arm, in,
d = cross sectional width of the mortar bedded area, parallel to the loading arm, in,
t_{fs} = minimum face shell thickness, in,
c = distance from the neutral axis to the most extreme tension fibre, in.

Statistical analysis was performed on the data. Mean, standard deviation and 95% confidence interval were calculated for each mortar and saturation type using Microsoft Excel.

RESULTS

In the 14 day tests the saturated Type N joints showed little change in strength with respect to unsaturated Type N joints. In the 28 day tests the average Type N saturated flexural strength was 85% of the unsaturated joints. The saturated Type S joints tested at 14 days exhibited a 25% decrease in flexural strength compared to the unsaturated capacity. At 28 days the saturated Type S joints had an average flexural strength equal to 115% of the unsaturated strength. The standard deviation ranged from 0.079 MPa to 0.134 MPa. Due to the small sample size the 95% confidence intervals are large. It is difficult to draw conclusions from such extreme intervals. The average strengths, standard deviations, and confidence intervals can be found in Table 2.

Table 2: Flexural Bond Strength by Mortar Type and Saturation Type, MPa (psi)

	14 DAYS				**28 DAYS**			
	Type N		**Type S**		**Type N**		**Type S**	
	Dry	**Saturated**	**Dry**	**Saturated**	**Dry**	**Saturated**	**Dry**	**Saturated**
AVERAGE	0.347 (50.26)	0.365 (52.87)	0.445 (64.51)	0.332 (48.17)	0.382 (55.34)	0.327 (47.34)	0.514 (74.58)	0.592 (85.90)
STD DEV	0.078 (11.24)	0.103 (14.90)	0.106 (15.31)	0.081 (11.72)	0.134 (19.38)	0.094 (13.68)	0.117 (16.99)	0.099 (14.39)
95% C.I.	0.347 ±0.152 (50.26 ±22.03)	0.365 ±0.201 (52.87 ±29.20)	0.445 ±0.158 (64.51 ±30.00)	0.332 ±0.158 (48.17 ±22.97)	0.382 ±0.262 (55.34 ±37.98)	0.327 ±0.185 (47.34 ±26.80)	0.514 ±0.230 (74.58 ±33.30)	0.592 ±0.195 (85.90 ±28.20)

The measured flexural strength values appear to agree with previously reported data sets. Wood's compilation of data sets (generated prior to 1995) reported flexural strength values for Type N Portland Cement/Lime mortars ranging from 0.33 to 1.25 MPa with a mean flexural strength of 0.64 ± 0.19 MPa [6]. Flexural strength measurements for Type S Portland Cement/Lime mortars ranged from 0.37 to 1.83 MPa with a mean flexural strength of 0.87 ± 0.27 MPa.

DISCUSSION

The average tensile flexural bond strength of Type N mortar was less than the tensile flexural strength of Type S mortar. In addition both dry mortars increased strength from 14 to 28 days.

These results are consistent with the expected behaviour determined from the literature review. The results show changes in the behaviour of the saturated mortar between the 14 day test and the 28 day test, particularly in the Type S construction. Type S experienced a decrease in strength due to saturation after 14 days and an increase of strength due to saturation after 28 days. Deviations from the ASTM standards may account for the inconsistencies and include use of a manually operated hydraulic jack, which did not allow for the allowable loading rate and relying on the experience of a mason rather than quantitative checks. In addition a bearing plate was not used for the 14 day tests.

The influence of curing conditions on flexural strength has previously been investigated in several studies [7, 13]. In a study of clay brick prisms constructed with Type N and S mortars, McGinley found that the flexural bond strength appeared to decrease at high and low initial rates of absorption (IRAs) [14]. It was believed that high IRAs resulted in micro-crack formation at the brick-mortar interface. At low IRAs, the mortar penetration into the brick was too shallow, decreasing the number of cement hydration products able to form and bind the brick to the mortar slab. It is possible that the complete saturation of prisms during curing also influenced these same micro-scale mechanics cited by McGinley.

ASTM Standard C1357 uses a comparison of coefficients of variation to assess the precision of bond strength data sets [15]. Hedstrom et al. utilized a similar testing procedure to evaluate the statistical variance of prisms constructed with Portland cement- hydrated lime mortars tested at three laboratories [3]. Their testing found coefficients of variation between 9.3% and 25%. Melander et al. performed a similar study to evaluate the variation in prisms constructed with Type N, S and M mortars. They reported coefficients of variation for Type N and S mortars from 12% to 36% and from 14% to 25%, respectively. In this paper, results show coefficients of variation ranging from 17% to 35 % [16]. While these values are at the higher end of the previously reported ranges, the larger coefficients of variation could be an artefact of a smaller number of joints used in the flexural strength determinations.

In addition, 1989 tests subjecting masonry walls to a 72 hour water penetration test, recorded permeation of the mortar [17]. The tests showed that the water penetrated through the entire length of the head joint but often failed to permeate through the bed joint. Although submersion allows the water to permeate from both sides of the bed joints, it is possible that 48 hours did not provide enough time for the water to fully saturate the mortar and the full effects of saturation were not observed.

CONCLUSIONS

Differences in the values of dry and saturated prisms indicate that saturation has some effect on the tensile flexural bond strength of clay masonry prisms. After 14 days of curing, results show an increase in flexural strength for Type N saturated prisms and a decrease in flexural strength for Type S saturated prisms. After 28 days, the standard-prescribed curing time, results appear to indicate that this trend has reversed. Type N saturated prisms showed a decrease in flexural strength and Type S saturated prisms showed an increase in flexural strength. Given that results here reported do not allow speaking with statistical certainty, it is recommended that additional tests be performed to better understand the behaviour. Tests are recommended to include larger batch sizes, 72 hour submersion period, and more stringent quality control.

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