The Effect of Robotic Brick Placement on Bond Strength

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Abstract

Several factors can affect the bond strength of brick masonry units. Some of these factors include: Initial rate of absorption (IRA) of water for bricks, brick porosity, brick texture, type of mortar, type of sand, mix proportions, mortar water content, mortar workability, mortar viscosity, time between the application of mortar and placement of the brick, and the placement method. This paper presents a research study conducted to determine the effect of robotic brick placement on the bond strength using the Bond Wrench Test as described in ASTM C1072.

1: INTRODUCTION

The issue of creating an efficient bond between bricks using mortar has been studied in great detail [4] [6]. One of the leaders in this field is the Ceramic Engineering Department at Clemson University. Most recently, D. Mehrotra [4] and G. Robinson [6] have done extensive testing to determine the factors that affect the bond strength of brick masonry units. Mehrotra [4] found that the following major characteristics affect bond strength:

1. Initial rate of absorption of water for bricks
2. Brick porosity
3. Brick texture
4. Type of mortar
5. Type of sand
6. Mix proportions
7. Mortar water content
8. Mortar workability
9. Mortar viscosity
10. Use of clay and/or use of fly ash in the mortar mix

Other factors which affect bond strength include the method of formation, and time between the application of the mortar and the placement of the brick.

According to Robinson [6], the brick to mortar bond is a mechanical bond produced by the intrusion of a cementitious paste into the pores of the brick. Therefore, it is vital that this paste be able to flow into such pores. The IRA (Initial Rate of Absorption) of the brick is important because high IRA bricks may draw water from the mortar, thus preventing the cementitious paste from flowing into brick pores. This can be counteracted by increasing the water content of the mortar or by aggressive placement methods. Low IRA bricks tend not to absorb water and therefore do not obtain sufficient intrusion. The same study [6] examined the effect of different placement methods which included:

1. Pressing the brick into place
2. Placing the brick with load
3. Placing the brick without load
4. Vibrating the brick into place
5. Tapping the brick

Generally, it was found that the amount and type of load applied to the brick affects the bond strength. Pressing the brick into place and the vibration method were both found to provide a consistently high bond strength. It is suggested that the placement procedure can mask the effects of IRA and water content of the mortar. For general use, a medium IRA brick was recommended.

2: EXPERIMENTAL SETUP

Figure 1 represents a schematic of the apparatus used to collect the bond strength values using the Bond Wrench Test as described in ASTM C1072 [1].

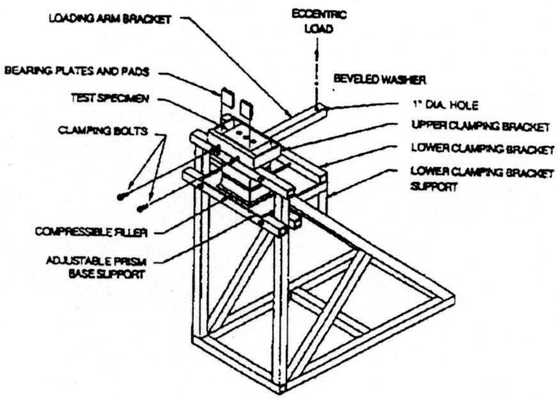

Figure 1: Schematic of Bond Wrench Test Apparatus (Source: ASTM C1072)

The test apparatus consists of a metal frame designed to support a prism. The support system is adjustable to prisms ranging in height from two to seven masonry units. The upper clamping bracket that is clamped to the top masonry unit of the prism does not come into contact with the lower clamping bracket during the test. After the prism has been placed in the support frame, the lower and upper clamping brackets hold the prism firmly in a locked position. A load is then applied at a slow and uniform rate until failure occurs. Figure 2 presents a photograph of the apparatus.

Figure 2: Bond Wrench Test Apparatus

The two clamping brackets are clearly visible at the top of the frame. The upper clamping bracket is attached to the base of the metal frame with two metal pipes connected by an electronic load cell. The load is applied by turning a wrench attached to the upper clamping bracket. Figure 3 shows a two-brick masonry prism placed in the support frame.

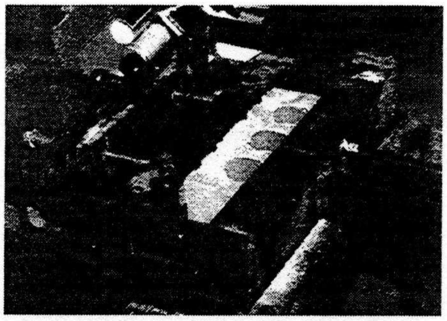

Figure 3: Prism Ready to be Tested

Once the prism is placed vertically on the metal frame, it is clamped firmly into a locked position using the lower clamping bracket. The prism is oriented so that the face of the joint intended to be subjected to flexural tension is on the same side of the specimen as the clamping screws. The prism is positioned at the required elevation resulting in a single brick projecting above the lower clamping bracket. A piece of polystyrene, a soft bearing material, is placed between the bottom of the prism and the adjustable prism base support. The upper clamping bracket is then attached to the top brick. Each clamping bolt is then tightened using a torque of 5.7 N·m. The load is then applied at a uniform rate so that the total load is applied in between 1 and 3 minutes. The load is measured by an electronic load cell. Figure 4 shows the load cell as part of the Bond Wrench Test apparatus.

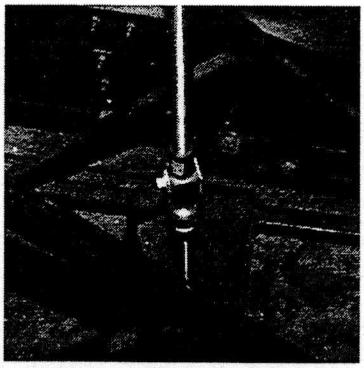

Figure 4: Electronic Load Cell

The load cell shown in Figure 4 has a maximum load capacity of 905 kg. The load readings were collected by connecting the load cell to an analoginput data acquisition board that was connected to a PC. The load cell was calibrated so as to give a 24mV output reading corresponding to a 905 kg load.

3: DATA COLLECTION

According to ASTM C1072 [1], the net area of brick determines the equation to use to calculate the bond strength value. The bricks used in the bond wrench experiments have the following dimensions [5]:

- Average Width = 8.61 cm
- Average Length = 19.35 cm
- Average Diameter of Hole #1 = 3.58 cm
- Average Diameter of Hole #2 = 3.15 cm
- Average Diameter of Hole #3 = 3.58 cm

Based on the previous numbers, the following parameters can be determined:

- Total Surface Area $= 8.61cm \times 19.35cm = 166.60cm^2$
- Total Hole Area

$$= \Pi\left[\left(\frac{3.58cm}{2}\right)^2 + \left(\frac{3.15cm}{2}\right)^2 + \left(\frac{3.58cm}{2}\right)^2\right] = 27.94cm^2$$

- Net Brick Area

$$= 166.60cm^2 - 27.94cm^2 = 138.66cm^2$$

- % Net Brick Area $= \left(\frac{138.66cm^2}{166.60cm^2}\right) \times 100 = 83.23\%$

Since the value of Percent Net Brick Area (i.e., 83.23%) is greater than 75%, the masonry units are considered solid rather than hollow. Therefore the following equation will be used to calculate the bond strength (gross area flexural tensile strength):

$$F_g = \left[\frac{6(PL + P_1L_1)}{bd^2}\right] - \left[\frac{(P + P_1)}{bd}\right] \qquad \text{(Eq. 1)}$$

where: F_g=gross area flexural tensile strength, (psi)
P=maximum applied load, (lbf)
P_1=weight of loading arm, (lbf)
L=distance from center of prism to loading point, (in.)
L_1=distance from center of prism to centroid of loading arm, (in.)
b=average width of cross section of failure surface, (in.)
d=average thickness of cross section of failure surface, (in.)

For this experimental setup, a number of terms in Eq. 1 have constant values:

P_1=180 N
L=33.50cm
L_1=0.48cm
b=19.35cm for manual brick placement
=17.78cm for robotic brick placement
d=0.95cm for manual and robotic brick placement

From previous research data [3], the average of the bond strength test results were 673 kPa with a coefficient of variation (cov) of 0.182. Therefore, the standard deviation (σ) of the data would be equal to (0.182)*(673 kPa)=122.49 kPa. Furthermore, the variability of the predicted value of the bond strength (d) (with 95% confidence) would be:

$$d = \pm t(0.975, \infty)(\sigma)\sqrt{\frac{1}{n}}$$

$$= \pm(1.96)(122.49)\sqrt{\frac{1}{n}}$$

$$= \pm 240.08\sqrt{\frac{1}{n}}$$

Table 1 presents the predicted value of the bond strength (d) as related to the number of tests.

Table 1: Predicted Value of the Bond Strength as related to Number of Tests

n	±d (kPa)
1	240.12
2	138.63
5	107.41
7	90.74
10	75.93
15	62.01
30	43.82

ASTM C1072 [1] states that a minimum of five tests should be conducted. According to the calculations in Table 1, ten tests are needed in order to compare robotic vs. manual brick placement. Therefore, with 95% confidence, the predicted value of the bond strength will be ±75.93 kPa. Ten experiments were conducted with the robot arm, and another ten experiments with a "qualified" mason placing bricks using his normal style. In all twenty experiments, the brick-mortar bond strength was measured. Figure 5 shows the randomly selected bricks used in the experiments.

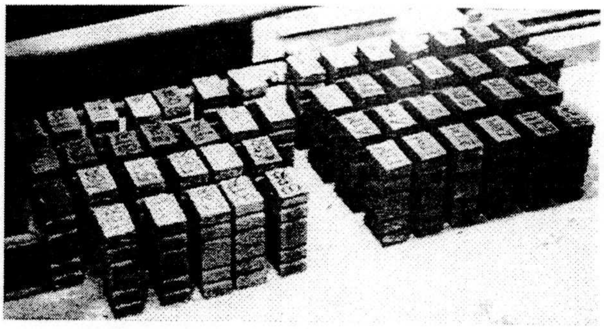

Figure 5: Bricks Selected for the Bond Strength Experiments

For the manual brick placement experiments, the services of a "qualified" mason were utilized. The mason has 15 years of experience in brick and block masonry, and has worked on more than 1000 masonry jobs since 1980.

For the first robotic brick placement experiments, a mold was used to create the mortar bed joint. Figure 6 shows a sketch of the mold.

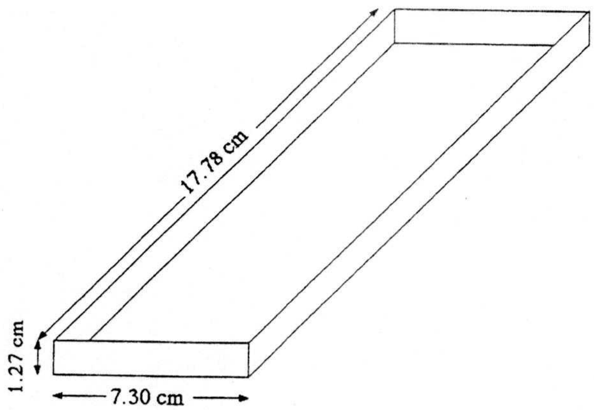

Figure 6: First Robotic Placement Mortar Mold

The 7.30 cm wide - 1.27 cm thick mold was fabricated from stainless steel. The length of the mold was 17.78 cm so as to fit the length of the brick. ASTM C1072 requires the mortar joint to be 3/8 in. (0.95 cm) thick. An additional 1/4 in. (0.64 cm) was added to the mold thickness so as to allow for the compression of the mortar joint during brick placement. Prior to robotic placement, the mold was placed onto the bottom brick then filled with mortar using a trowel. Thereafter, the mold was removed before a brick was robotically placed onto the bed joint.

Ten prisms were built manually and another ten were built robotically. According to ASTM C1072, all prisms were cured for seven days, then tested using the Bond Wrench Test apparatus. During the 7 day curing period, all prisms were placed inside white plastic trash bags as shown in Figure 7.

Figure 7: Trash Bags containing the Masonry Prisms During the 7-Day Curing Period

Table 2 presents the bond strength measurements for both manual and robotic brick placement.

Table 2: Bond Strength Measurements for Manual and Robotic Placement

Prism #	Bond Strength Meas. (kPa)	
	Manual Pl.	Robotic Pl.
1	40230.33	212.61
2	43451.36	4319.05
3	43831.20	212.61
4	42848.68	21268.45
5	52005.32	47588.25
6	21906.92	14521.76
7	33372.98	212.61
8	36290.14	4148.17
9	21744.85	212.61
10	23294.59	6623.06
Average:	35897.64	9931.92
Variance:	11.20E+07	22.46E+07

As shown in Table 2, the average value of the manual placement bond strength is 35897.64 kPa compared to 9931.92 kPa for robotic placement. The variance value for the manual placement measurements is 11.20E+07 as opposed to 22.46E+07 for the robotic placement measurements.

Clearly, the bond strength measurements using manual placement are higher and more consistent than those using robotic placement. After close observation of both kinds of prisms, it seemed that the lack of performance of the robotically placed prisms was due to the flat bed joint placed using the mold shown in Figure 6. In fact, some of the robotic prisms fell apart prior to testing. During manual placement, the mason applied an uneven bed joint with a considerably larger thickness than 1/2 in. (1.27 cm). Once the top brick was placed and the bed joint compacted to a thickness of 3/8 in. (0.95 cm), mortar was pushed into the holes of the top brick. This was clearly noticed on the tested manual prisms, and was definitely lacking in the robotic prisms since the molded bed joint was flat. Accordingly, a second mold was fabricated that resembled the manually placed bed joint. Figure 8 shows a sketch of the second mold.

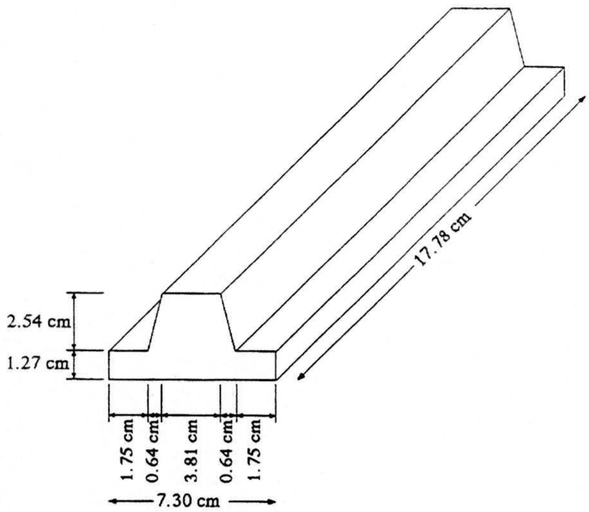

Figure 8: Second Robotic Placement Mortar Mold

As seen in Figure 8, the second mold includes a "bump" in the middle of the section that would be aligned with the holes of the top brick in order to allow mortar to enter them. Ten prisms were built using this mold. After a curing period of seven days, the prism were tested using the bond wrench test apparatus. Table 3 presents the bond strength measurements for the robotic brick placement prisms using the second mold.

Table 3: Bond Strength Measurements for Robotic Placement using the Second Mold

Prism #	Bond Strength Meas. (kPa) Robotic Placement (Second Mold)
1	11368.89
2	20981.82
3	15447.77
4	5735.63
5	10812.18
6	19173.89
7	33516.11
8	39149.37
9	30313.64
10	22023.59
Average:	20852.29
Variance:	11.53E+07

As shown in Table 3, the average value of the robotic placement bond strength using the second mold is 20852.29 kPa with a variance of 11.53E+07. Comparing the second robotic bond strength measurements to the first values reveals that the average bond strength value was nearly twice that of the first mold, while the variance in the second measurements was nearly cut in half. This significant improvement can be credited to the second mold which allowed mortar to enter the holes of the top brick and create a stronger bond.

4: DATA ANALYSIS

The average and variance values of the bond strength measurements for the different placement methods can now be compared. Figure 9 presents a bar chart illustrating the average bond strength values for different placement methods.

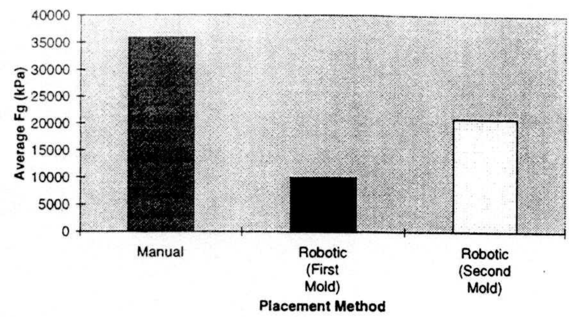

Figure 9: Average Values of F_g for Different Placement Methods

As presented in Figure 9, the average bond strength value for manual placement is the highest, followed by the second robotic, then by the first robotic. It is clearly discernible that the average bond strength was almost doubled using the second mold. Figure 10 presents a bar chart showing the variance in the bond strength values for different placement methods.

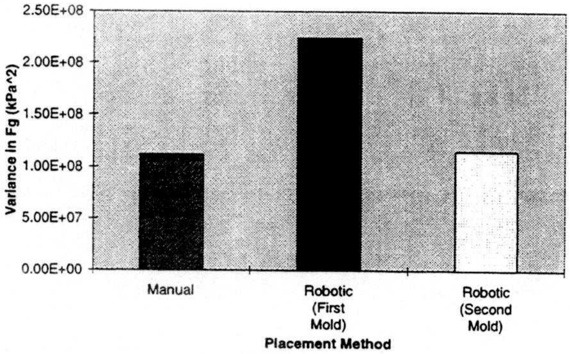

Figure 10: Variance in F_g Values for Different Placement Methods

As shown in Figure 10, the variance in the bond strength values for the first robotic placement is the highest followed by the second robotic and the manual. The variance in bond strength measurements is almost equal for the manual and the second robotic placement methods.

Hypothesis testing was conducted on the second robotic and manual bond strength data to compare the means (μ_R and μ_M) and the variances (σ_R^2 and σ_M^2) of the two samples. Table 4 presents a summary of a two-sample hypothesis test of the mean.

Table 4: Summary of a Two-Sample Hypothesis Test of the Mean [2]

Step 1:	State the hypothesis to be tested. H_o: $\mu_R > \mu_M$ H_1: $\mu_R < \mu_M$
Step 2:	Select a preplanned $\alpha = 0.01$
Step 3:	Compute the test statistic: $t_o = \frac{(Y_R - Y_M)}{S_p\sqrt{\left[\left(\frac{1}{n_R}\right)+\left(\frac{1}{n_M}\right)\right]}}$, where $S_p = \sqrt{\frac{(n_R - 1)S_R^2 + (n_M - 1)S_M^2}{(n_R - 1) + (n_M - 1)}}$
Step 4:	Use percentiles of the t distribution with $v = n_R + n_M - 2$ degrees of freedom to estimate the area to the left of t_o.
Step 5:	P = area in step 4.
Step 6:	If $P < \alpha$, conclude H_1 with (1-P)100% confidence. If P ³ α, fail to reject H_o.

In step 2, α is the probability of committing a Type I error (i.e., concluding H_1 when the true state of nature is H_o). α is set at a minimum level, usually 0.05, 0.01, or 0.001, depending on the degree of criticality of such an error (i.e., in academia and social sciences α is usually 0.05; whereas, in hospital tests or other critical areas of testing, α is either 0.01 or 0.001). In step 3, S_p represents the pooled standard deviation of the two samples. It is equal to the square root of a weighted average of the two variances [2] Table 5 presents a summary of a two-sample hypothesis test of the variance.

Table 5: Summary of a Two-Sample Hypothesis Test of the Variance [2]

Step 1: State the hypothesis to be tested.

$H_o: \sigma_R^2 < \sigma_M^2$

$H_1: \sigma_R^2 > \sigma_M^2$

Step 2: Select a preplanned $\alpha = 0.01$

Step 3: Compute the test statistic:

$$F_o = \frac{S_R^2}{S_M^2}$$

Step 4: Using an F distribution with $v_R = n_R - 1$ and $v_M = n_M - 1$, estimate the area in the tail.

Step 5: P = area in step 4.

Step 6: If $P < \alpha$, conclude H_1 with (1-P)100% confidence.

If P ³ α, fail to reject H_o.

Table 6 presents the results of the hypothesis analysis. The first column shows the ten bond strength measurements for robotic placement using the second mold. The second column displays the measurements for manual placement.

Table 6: Hypothesis Analysis of Bond Strength Data

Robotic	Manual	Two-Sample Hyp. Test (Mean)		
11368.89	40230.33		*Robotic*	*Manual*
20981.82	43451.36	Mean	20852.29	35897.64
15447.77	43831.20	Var.	11.53E+07	11.20E+07
5735.63	42848.68	Obs.	10	10
10812.18	52005.32	df	18	
19173.89	21906.92	α	0.01	
33516.11	33372.98	t	-3.16	
39149.37	36290.14	P(T<=t)	28.84E+4	
30313.64	21744.85			
22023.59	23294.59			
		Two-Sample Hyp. Test (Var.)		
			Robotic	*Manual*
		Mean	20852.29	35897.64
		Var.	11.53E+07	11.20E+07
		Obs.	10	10
		df	9	9
		α	0.01	
		F	1.03	
		P(F<=f)	48.33E+2	

To the right of the second column in Table 6 are the results of the two-sample hypothesis tests for the mean and variance. According to Step #6 in the summary explained in Table 4, P is less than α. This allows us to conclude H_1 with (1-P)% = 99.71% confidence, i.e., the population mean for the robotically placed bond strength measurements is less than those of the manually placed. The fact that the bond strength values for the second robotic prisms were nearly twice that of the first robotic prisms is in itself a significant contribution. An optimal shape and size of a mold can be found to create a sufficiently strong bond. This could be one area where further research can be applied in the future.

In the two-sample hypothesis test for the variance, it was found that P is greater than α. According to Step #6 in Table 5, H_o cannot be rejected. Therefore, the population variance for the robotically placed bond strength measurements is less than those of the manually placed. This represents a crucial finding in showing that bond strength values are more consistent when prisms are placed robotically than when placed manually.

5: CONCLUSION

In order to analyze the effect of robotic brick placement on bond strength, ten prisms were built manually and another ten were built robotically. Hypothesis testing was conducted to compare the means and variances of the two samples. It was concluded with 99.71% confidence that the population mean for the robotically placed bond strength measurements was less than those of the manually placed. On the other hand, the population variance for the robotically placed bond strength measurements was less than those of the manually placed. This shows that bond strength values are most consistent when prisms are placed robotically than when placed manually.

6: ACKNOWLEDGMENTS

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