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# EFFECT OF FABRICATION AND CURING ON BOND STRENGTH OF MASONRY

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## ABSTRACT

This paper focuses on the relationship between the bond strength of masonry assemblies and fabrication and curing techniques used to construct and condition test assemblies. The study was conducted using concrete masonry brick units and clay masonry units. Variables investigated included: altering the moisture condition of units when laid, using different mortar bedding techniques to fabricate specimens, finishing mortar joints using concave tooling versus striking the joint flush with the face of units, and employing different curing procedures during the time period between fabrication and testing of specimens. Of the variables evaluated in this study, unit conditioning and curing procedures have the greatest influence on the development of bond strength.

The paper is based on experimental work conducted by Holnam, Inc. at Holly Hill, South Carolina, USA. Experimental methods, data, results, and conclusions are included in the paper.

## INTRODUCTION

For many years bond of mortars to units has been the focus of much research and discussion. The term *bond* refers to a specific property that can be subdivided into: (1) extent of bond, or degree of contact of the mortar with the masonry units; and (2) bond strength, or the adhesion of mortar to units. Both are functions of many factors associated with the specific mortar and units considered, as well as the conditions under which they are assembled and cured. The discussion in this paper focuses on bond strength and investigates

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relationships between specific parameters and measured bond strength test results.

The data presented in this paper are from two experimental programs conducted by Holnam, Inc. at Holly Hill, South Carolina. The first, conducted in the summer of 1993, involved measuring the flexural bond strength of clay brick masonry prism specimens. Parameters investigated as variables included: tooling of joints, conditioning of units, and mortar bedding technique. Discussion of procedures, results and conclusions with respect to that testing program (Phase I) is presented in this paper.

The second series of tests, conducted during the summer of 1994, involved measuring the flexural bond strength of concrete masonry brick prism specimens. Parameters investigated as variables included conditioning of unit prior to fabrication and curing environment between the time of fabrication and testing. Discussion of procedures, results, and conclusions with respect to this testing program (Phase II) is also presented in this paper.

## TEST PROCEDURES

In both Phase I and Phase II, six-unit high stacked-bond prism specimens were fabricated for bond strength testing. Mortar consisted of 1 part Type S masonry cement (ASTM C91) and 3 parts masonry sand by volume. Mortars were mixed in a mechanical mixer to a workable consistency as judged by an experienced mason. The masonry sand met the gradation requirements of ASTM C 144. All prisms were constructed indoors in laboratory conditioned air. The mason constructed three prisms for each test condition, thus a single test set consisted of a total of fifteen joints.

*Phase I*
ASTM C 216 grade SW clay masonry units having a moderate initial rate of absorption (IRA of 15 gm/min · 30 sq. in.) were combined with Type S masonry cement mortar. The clay masonry units were of a single brand, source, and shipment.

Prism specimens were constructed in open plastic bags which were immediately sealed upon completion of fabrication. Specimens were removed from the plastic bags just prior to testing using the bond wrench. All prism specimens were fabricated in a single day. Flexural bond strength measurements were made 14 days after the prism specimens were constructed. Remaining procedures outlined in ASTM C 1072, the Standard Method for Measurement of Masonry Flexural Bond Strength, were followed in determining flexural bond strengths.

Units were preconditioned to either a "wet" or "dry" state. "Dry" units were allowed to stand several days in laboratory air to reach equilibrium temperature and humidity. "Wet" units were taken from the stock of "dry" units and allowed to soak in water for at least 2 hours. "Wet" units were then allowed to stand in laboratory air approximately 1 hour prior to fabrication of prisms.

Mortar joints were either tooled with a concave jointer or struck flush using a trowel.

Three techniques were used in placing bedding mortar on units, resulting in the mortar bedding surface having either a furrowed, peaked, or flat surface prior to placement of the next unit (see Fig. 1).

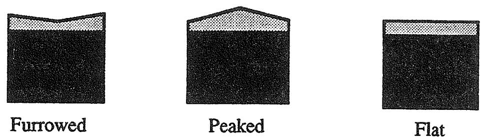


Fig. 1 - Three Mortar Bedding Techniques (end view)

These variables were incorporated in the experimental program for phase I, as summarized in Table 1. The test program for phase I is structured as a factored experiment investigating how three controlled variables affect the dependent variable, bond strength. Fixed levels were selected for the three factors, brick condition, tooling procedure, and bedding procedure.

Table 1 - Test Matrix for Phase I

| Test | Brick Condition | | Tooling | | Bedding | | |
|---|---|---|---|---|---|---|---|
| ID | Wet | Dry | Struck | Concave | Furrowed | Peaked | Flat |
| 1A | X | | X | | | | X |
| 1B | X | | | X | | | X |
| 1C | | X | X | | | | X |
| 1D | | X | | X | | | X |
| 2A | X | | X | | X | | |
| 2B | X | | | X | X | | |
| 2C | | X | X | | X | | |
| 2D | | X | | X | X | | |
| 3A | X | | X | | | X | |
| 3B | X | | | X | | X | |
| 3C | | X | X | | | X | |
| 3D | | X | | X | | X | |

*Phase II*

Concrete masonry brick of a single brand, source, and shipment were combined with the Type S masonry cement mortar. The ASTM C 55 grade N brick were purchased locally.

Units were preconditioned to: a saturated surface dry (SSD) state, an oven dry state, or a surface damp state. The SSD state was achieved by immersing the units in water for at least 2 hours. Approximately 1 hour prior to fabrication the units were taken out of the water and allowed to stand in the laboratory air until the mortar bedding surface was visibly dry.

Oven dry specimens were placed in a drying oven set at 110° C for 24 hours. At least 8 hours prior to fabrication of specimens, these units were taken out of the oven and allowed to stand in the open laboratory environment to reach ambient temperature prior to fabrication of prisms. The surface damp condition was achieved by using a paint brush to wet bedding surfaces of oven dry units immediately prior to placement.

Mortar joints were struck flush using a trowel and bedding mortar was applied such that a peaked mortar bed was achieved.

Prism specimens were subjected to one of three curing environments: laboratory air, moist room, or laboratory air–wet at 7 days. Laboratory air was maintained at a temperature of 22.8 ± 1.7° C (73 ± 3° F) and a relative humidity of 55 ± 5 percent. The moist room environment met the requirements of ASTM C 511. Moist room cured specimens were placed in the moist room 24 hours after fabrication and removed from the moist room 21 days after fabrication. They were then stored in the laboratory air until tested. Specimens cured according to the "laboratory air–wet at 7 days" procedure were spayed with water until saturated using a garden hose.

Variables were incorporated in the experimental design for phase II as summarized by Table 2. The overall program for phase II is structured as a factored experiment with bond strength as the dependent variable. Fixed levels were selected for the two variables, unit condition and curing procedure. Three levels were selected for unit condition, and three levels for curing. However, for the curing level "laboratory air–wet at 7 days" no combinations were incorporated with two of the unit condition levels.

Table 2 - Test Matrix for Phase II

| Test ID | Unit Condition | | | Curing | | |
|---|---|---|---|---|---|---|
| | SSD | Oven Dry | Surface Damp | Lab Air | Moist Room | Lab Air Wet @ 7 D |
| A | X | | | X | | |
| B | X | | | | X | |
| C | | X | | X | | |
| D | | X | | | X | |
| E | | X | | | | X |
| F | | | X | X | | |
| G | | | X | | X | |

All specimens were constructed over a two day period, and flexural bond strength measurements were made 28 days after the prism specimens were fabricated. Procedures outlined in ASTM C 1072, the Standard Method for Measurement of Masonry Flexural Bond Strength, were followed in determining flexural bond strengths.

## RESULTS

*Phase I*

Flexural bond strength results are presented in Table 3. The overall average bond strength of all tests was 505 kPa (73 psi). The average standard deviation for each set of 15 mortar joints was 130 kPa (19 psi) and the average coefficient of variation for each set of 15 mortar joints was 26 percent. The within-test variability exhibited by these data is consistent with that encountered in other studies, given that the number of mortar joints tested in each set was limited to 15 (Hedstrom et al. 1991), (Melander et al. 1993), (McGinley 1993), and (McGinley 1994).

Table 3 - Flexural Bond Strength Results from Phase I

| Test ID | Fabrication Procedure | | | Flexural Bond Strength Data | | | |
|---|---|---|---|---|---|---|---|
| | Brick Condition | Tooling | Bedding | N* | Average kPa (psi) | Std Dev kPa (psi) | COV % |
| 1A | Wet | Struck | Flat | 15 | 525 (76) | 162 (24) | 31 |
| 1B | Wet | Concave | Flat | 15 | 533 (77) | 157 (23) | 29 |
| 1C | Dry | Struck | Flat | 15 | 494 (72) | 135 (20) | 27 |
| 1D | Dry | Concave | Flat | 15 | 394 (57) | 115 (17) | 29 |
| 2A | Wet | Struck | Furrow | 15 | 558 (81) | 181 (26) | 32 |
| 2B | Wet | Concave | Furrow | 15 | 511 (74) | 125 (18) | 24 |
| 2C | Dry | Struck | Furrow | 15 | 424 (62) | 87 (13) | 21 |
| 2D | Dry | Concave | Furrow | 15 | 461 (67) | 84 (12) | 18 |
| 3A | Wet | Struck | Peaked | 15 | 570 (83) | 128 (19) | 23 |
| 3B | Wet | Concave | Peaked | 15 | 557 (81) | 131 (19) | 24 |
| 3C | Dry | Struck | Peaked | 15 | 510 (74) | 94 (14) | 18 |
| 3D | Dry | Concave | Peaked | 15 | 521 (76) | 151 (22) | 29 |

*N = number of joints tested

The effect of bedding, brick condition, and tooling on bond strength is presented in Table 4. Table 5 indicates the number of joints represented by the average values listed in Table 4. For example, test results from fifteen joints (Test 1D) were averaged to yield the average value listed in row 1, column 1 of Table 4. That entry is for specimens constructed using dry brick, a concave joint, and the flat bedding technique.

Table 4 - Average Flexural Bond Strengths - Phase I, kPa (psi)

| Bedding | Brick Condition, Tooling | | | | | | Grand Avg. |
|---|---|---|---|---|---|---|---|
| | Dry | | | Wet | | | |
| | Concave | Struck | Con & Str. | Concave | Struck | Con & Str. | |
| Flat | 395 (57) | 495 (72) | 440 (64) | 530 (77) | 525 (76) | 530 (77) | 490 (71) |
| Furrow | 460 (67) | 425 (62) | 440 (64) | 510 (74) | 560 (81) | 530 (77) | 490 (71) |
| Peaked | 525 (76) | 510 (74) | 515 (75) | 560 (81) | 570 (83) | 565 (82) | 540 (78) |
| Grand Avg. | 455 (66) | 475 (69) | 470 (68) | 530 (77) | 550 (80) | 545 (79) | 505 (73) |

Table 5 - Number of Test Joints Tested for Averages Listed in Table 4

| Bedding | Brick Condition, Tooling | | | | | | Grand Avg. |
|---|---|---|---|---|---|---|---|
| | Dry | | | Wet | | | |
| | Concave | Struck | Con & Str. | Concave | Struck | Con & Str. | |
| Flat | 15 | 15 | 30 | 15 | 15 | 30 | 60 |
| Furrow | 15 | 15 | 30 | 15 | 15 | 30 | 60 |
| Peaked | 15 | 15 | 30 | 15 | 15 | 30 | 60 |
| Grand Avg. | 45 | 45 | 90 | 45 | 45 | 90 | 180 |

Table 6 - Deviation of Averages from Overall Average - Phase I
kPa (psi)

| Bedding | Brick Condition, Tooling | | | | | | Grand Avg. |
|---|---|---|---|---|---|---|---|
| | Dry | | | Wet | | | |
| | Concave | Struck | Con & Str. | Concave | Struck | Con & Str. | |
| Flat | -110 (-16) | -10 (-1) | -65 (-9) | +25 (+4) | +20 (+3) | +25 (+4) | -15 (-2) |
| Furrow | -45 (-6) | -80 (-11) | -65 (-9) | +5 (+1) | +55 (+8) | +25 (+4) | -15 (-2) |
| Peaked | +20 (+3) | -5 (-1) | +10 (2) | +55 (+8) | +65 (+10) | +60 (+9) | +35 (+5) |
| Grand Avg. | -50 (-7) | -30 (-4) | -35 (-5) | +25 (+4) | +45 (+7) | +40 (+6) | 0 (0) |

The difference between the average bond strength for each test condition listed in Table 4 and the overall average bond strength for all of the tests is presented in Table 6. As illustrated in Table 6 and Fig. 2, certain trends appear to be associated with the various test conditions. The lowest bond strength was obtained on specimens constructed with dry brick, using the flat bedding technique and the concave finish on the mortar joint. The highest bond strength was obtained on specimens constructed with wet brick using the peaked mortar bedding technique and a struck mortar joint. In general, specimens constructed with dry units tend to have lower bond strengths than those constructed with wet units. Specimens constructed using the peaked mortar bedding technique tend to have somewhat higher bond strengths than those constructed using either the flat or furrowed bedding procedure. No consistent trend is apparent with respect to the effect of finishing the joint to a concave or struck surface. That observation is consistent with results reported by de Vekey and Jun (de Vekey and Jun 1993).

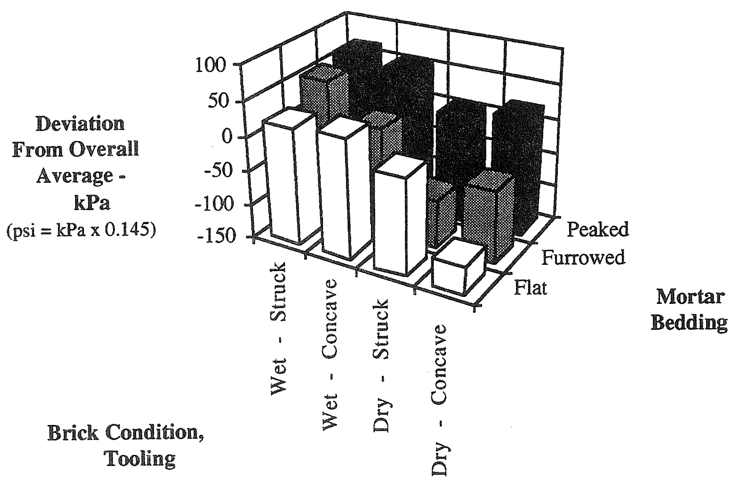


Fig. 2 Effect of Brick Condition, Tooling and Mortar Bedding on Flexural Bond Strength.

Analysis of variance as presented in Table 7 indicates that the main effects of brick condition and mortar bedding are significant at the 95% confidence level, although bedding technique just barely meets that confidence level. The effect of tooling is not significant nor do any of the interaction tests demonstrate significance. Additional statistical analysis of bedding effect levels confirms that the differences between bond strengths obtained using the peaked bedding technique compared to either the flat or furrowed technique are significant. The differences between bond strengths obtained using the furrowed technique and the flat technique are not significant.

Table 7 - Analysis of Variance - Phase I

| Source | df | Sums of Squares | Mean Square | F-ratio | Prob |
|---|---|---|---|---|---|
| BC | 1 | 252525 | 252525 | 14.367 | 0.0002 |
| Bdg | 2 | 107278 | 53639.1 | 3.0518 | 0.0499 |
| Tlg | 1 | 13868.9 | 13868.9 | 0.78906 | 0.3757 |
| Tlg*Bdg | 2 | 18618.4 | 9309.21 | 0.52964 | 0.5898 |
| Tlg*BC | 1 | 2.22222 | 2.22222 | 0.00013 | 0.9910 |
| Bdg*BC | 2 | 17027.5 | 8513.77 | 0.48438 | 0.6169 |
| Tlg*Bdg*BC | 2 | 72061.1 | 36030.5 | 2.0499 | 0.1320 |
| Error | 168 | 2952845 | 17576.5 | | |

BC = brick condition, Bdg = bedding technique, Tlg = tooling technique

*Phase II*

Table 8 presents results of flexural bond strength tests conducted in phase II of the test program. The overall average bond strength of all tests was 450 kPa (62 psi). The average standard deviation for each set of 15 mortar joints was 110 kPa (16 psi) and the average coefficient of variation for each set of 15 mortar joints was 26 percent. The within-test variability exhibited by these data is consistent with that encountered in other referenced studies (Hedstrom et al. 1991), (Melander et al. 1993), (McGinley 1993), and (McGinley 1994). It should

Table 8 - Flexural Bond Strength Results from Phase II, kPa (psi)

| Test ID | Unit Condition | Curing Condition | N | Average kPa (psi) | Std Dev kPa (psi) | COV % |
|---|---|---|---|---|---|---|
| A | Saturated Surface Dry | Laboratory Air | 15 | 566 (82) | 124 (18) | 22 |
| B | Saturated Surface Dry | Moist Room Removed to Laboratory Air at 21 Days | 15 | 424 (62) | 95 (14) | 22 |
| C | Oven Dry | Laboratory Air | 15 | 223 (32) | 70 (10) | 31 |
| D | Oven Dry | Laboratory Air Wet at 7 Days | 15 | 828 (120) | 200 (29) | 24 |
| E | Oven Dry | Moist Room Removed to Laboratory Air at 21 Days | 15 | 469 (68) | 94 (14) | 20 |
| F | Surface Damp | Laboratory Air | 15 | 181 (26) | 65 (9) | 36 |
| G | Surface Damp | Moist Room Removed to Laboratory Air at 21 Days | 15 | 453 (66) | 113 (16) | 25 |

be noted that the concrete masonry units used in this study were not the "standard concrete masonry units" used in those other studies, and thus the absolute bond values listed in Table 8 should not be compared to values obtained in those other studies.

The effect of unit condition and curing environment on bond strength is given in Table 9. Table 10 indicates the number of tests represented by the average values listed in Table 9.

Table 9 - Average Flexural Bond Strengths - Phase II, kPa (psi)

| Unit Condition | Curing Environment | | | Cumulative Avg. |
|---|---|---|---|---|
| | Lab Air | Lab Air Wet at 7 Days | Moist Room Removed to Lab Air at 21 Days | |
| Oven Dry | 225 (32) | 825 (120) | 470 (68) | 505 (73) |
| Surface Damp | 180 (26) | N/A | 455 (66) | 315 (46) |
| SSD | 565 (82) | N/A | 425 (62) | 495 (72) |
| Cumulative Avg. | 325 (47) | 825 (120)* | 450 (65) | 450 (65) |

*Represents only one set of prisms constructed using oven dry units.

Table 10 - Number of Joints Tested for Averages Listed in Table 9

| Unit Condition | Curing Environment | | | Cumulative Avg. |
|---|---|---|---|---|
| | Lab Air | Lab Air Wet at 7 Days | Moist Room Removed to Lab Air at 21 Days | |
| Oven Dry | 15 | 15 | 15 | 45 |
| Surface Damp | 15 | N/A | 15 | 30 |
| SSD | 15 | N/A | 15 | 30 |
| Cumulative Avg. | 45 | 15 | 45 | 105 |

The relationship between these variables and bond strength is illustrated in Table 11 and Fig. 3. Specimens that were wetted 7 days after being constructed using oven dry concrete masonry units achieved the highest bond strength values. The lowest bond strengths were obtained on laboratory air cured specimens constructed using oven dry and surface damp units. No increase in bond strength was evident when using surface damp units as compared to oven dry units in the laboratory air curing environment. Some increase in bond strength was observed for laboratory air cured specimens constructed using the saturated surface dry units as compared to air cured specimens

Table 11 - Deviation of Averages from Overall Average - Phase II
kPa (psi)

| Brick Condition | Curing Environment | | | Grand Avg. |
|---|---|---|---|---|
| | Lab Air | Lab Air Wet at 7 Days | Moist Room Removed to Lab Air at 21 Days | |
| Oven Dry | -230 (-33) | 375 (55) | 20 (3) | 55 (8) |
| Surface Damp | -270 (-39) | N/A | 5 (1) | -135 (-19) |
| SSD | 115 (17) | N/A | -25 (-3) | 45 (7) |
| Cumulative Avg. | -125 (-18) | 375 (55)* | 0 | 0 |

*Represents only one set of prisms constructed using oven dry units.

constructed using oven dry or surface damp units. Bond strength results on specimens cured in a moist room were fairly consistent and essentially independent of unit moisture condition.

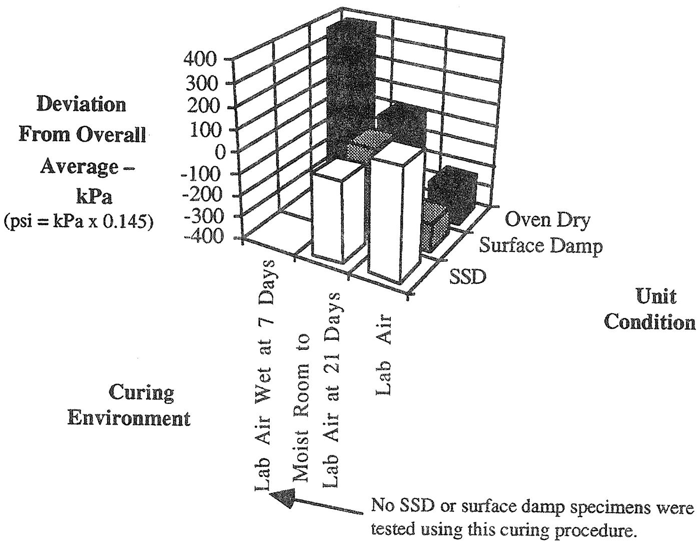


Fig. 3 Effect of Unit Condition and Curing Environment on Flexural Bond Strength.

As previously noted, only one level of unit condition (oven dry) was tested with the procedure of laboratory air curing specimens and wetting them at 7 days. Therefore an analysis of variance was performed on the data considering only two levels of curing, the laboratory air and the moist curing environment. Results of that analysis are presented in Table 12. Analysis of variance confirms that both curing environment and unit condition are significant factors affecting the measured bond strength of specimens. A significant interaction between curing environment and unit condition is also indicated. The analysis was extended to calculate expected mean cell values for the interaction of curing environment and unit condition. The nature of that

Table 12 - Analysis of Variance - Phase II

| Source | df | Sums of Squares | Mean Square | F-ratio | Prob |
|---|---|---|---|---|---|
| UC | 2 | 545940 | 272970 | 29.666 | ≤ 0.0001 |
| CE | 1 | 352063 | 352063 | 38.261 | ≤ 0.0001 |
| UC*CE | 2 | 804670 | 402335 | 43.725 | ≤ 0.0001 |
| Error | 84 | 772932 | 9201.58 | | |

UC = unit condition, CE = curing environment interaction is illustrated in Fig. 4 Moist curing clearly minimizes the influence of unit condition on bond strength.

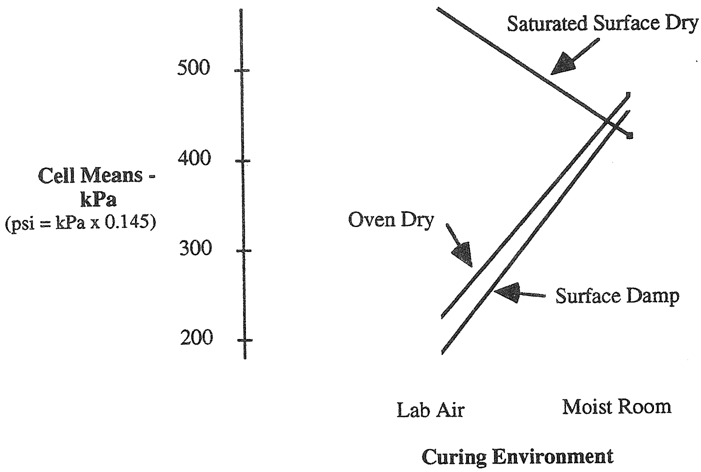


Fig. 4 Interaction Plot of Expected Cell Means for Levels of Curing Environment

## DISCUSSION

Curing environment has a dramatic effect on the development of bond strength. That fact is not surprising given the known role of curing in the development of strength in portland cement based mortar and concrete. However, it is interesting to note that in Phase II of this test program the best bond strength was obtained on a specimen that was constructed with an oven dry concrete masonry unit when the specimen was cured in laboratory air and then soaked at 7 days. Not only did the reintroduction of water reactivate strength development in the mortar, the bond strength achieved was greater than that achieved with specimens moist cured from 24 hours after fabrication. It may be that the combination of an absorptive unit and low humidity curing environment immediately after fabrication combined to pull paste from the mortar deeply into the pores of the unit and absorb water from that paste. Thus a dense paste, high in unhydrated cement particles was present at the interface and developed superior strength when saturated with water at 7 days. In any event, these results and those of a recent study reported by the National Concrete Masonry Association (Thomas 1994) would indicate that the development of bond strength interrupted by "dryout" can be rejuvenated by the introduction of water into the masonry.

The technique of dampening the surface of concrete masonry units just prior to fabricating specimens seems to offer no significant benefit to development of bond strength even in a low humidity air curing environment. Apparently the amount of moisture added to the system by this technique is not sufficient to aid in the curing of the mortar. The use of saturated surface dry units in a low humidity air curing environment did improve bond strength development. However, these specimens were unrestrained. In actual construction the use of such units would be expected to increase the probability of shrinkage cracking in the masonry.

## CONCLUSIONS

The following summarizes findings of this investigation:

1. Factors exhibiting an influence on bond strength development of masonry assemblies include curing environment, unit moisture condition, and mortar bedding technique.

2. Masonry specimens subjected to low humidity air curing yield relatively low bond strengths compared to the potential of the materials as achieved by moist curing or wetting specimens after fabrication.

3. Bond strength development of masonry specimens subjected to low humidity air curing can be greatly enhanced by wetting the specimens several days after fabrication.

4. Dampening the surface of concrete masonry units with a paint brush or roller is not effective in improving the bond strength development of a concrete masonry assembly subjected to low humidity air curing. Under dry conditions, spraying the masonry assembly after construction to restore moisture lost to evaporation is much more effective.

5. No significant difference in bond strength was observed between specimens tooled to produce a concave joint and those struck flush.

6. For clay masonry specimens, somewhat higher bond strengths were achieved in specimens constructed using wet units than in those constructed using dry units, and slightly higher bond strengths were achieved in specimens constructed using the peaked mortar bedding technique than in those constructed using either flat or furrowed mortar bedding techniques.

7. Moist room curing minimizes the influence of unit moisture condition on bond strength development.

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