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HOLLOW UNIT BOND WRENCH TEST TRIALS

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ABSTRACT

In an effort to determine the effectiveness of a proposed hollow unit bond wrench test apparatus, an investigation was proposed. This investigation compared the flexural tensile bond of face shell bedded, four high, stack bonded prisms, constructed with 150 mm, or 200 mm x 400 mm concrete masonry units measured using the procedures in ASTM Standard E 518 to that measured by a bond wrench testing apparatus on two high stack bonded prisms. These tests evaluated a total of two unit sizes and three mortar types at an age of 28 days.

This investigation found that the flexural tensile bond strengths measured using the bond wrench testing apparatus were lower than those measured using the ASTM E 518 procedures. The bond wrench test values appear to be about ½ those measured by the E 518 tests. In addition, the bond wrench test results have higher coefficients of variation than the ASTM E 518 test procedures, and the 150 mm (6 in.) hollow concrete masonry specimens appear to produce high flexural strengths and lower coefficients of variation than for those made with 200 mm (8 in.) units. The observed differences between the flexural tensile bond measured by the two test apparatus may be due to differences produced by the fabrication/curing procedures and specimen size. Further study is required before the proposed bond wrench can be effectively used to predict the flexural tensile bond strength of hollow unit masonry.

KEYWORDS: hollow unit, flexural, bond, testing

INTRODUCTION

In an effort to determine the effectiveness of the hollow unit bond wrench test apparatus and provide input towards improvements of this apparatus, a pilot-testing program was proposed. This testing program was to:

1. Construct four high, stack bonded prisms with face shell bedding using 150 mm (6 in.), or 200 mm (8 in.) x 400 mm (16 in.) units (Certified ASTM C 90 Standard Specification for Load bearing Concrete Masonry Units [1]) from a single source and cure in plastic bags in lab air.

2. Construct a number of two high stack bonded prisms with face shell bedding using 150 mm (6 in.), or 200 mm (8 in.) x 400 mm (16 in.) concrete masonry units (Certified ASTM C 90 Block from a single source) and cure in plastic bags in lab air.
3. After a minimum of 28 days of bag cure, test the four high prisms using the procedures in ASTM E 518 Standard Test Methods for Flexural Bond Strength of Masonry [1].
4. Also test each joint of the couplet prisms with the proposed bond wrench testing apparatus after a minimum of 28 days of curing.
5. Repeat the above tests for a total of two unit sizes and three mortar types.

TESTING PROGRAM

A total of fifteen, two high, face shell bedded prisms were fabricated for each of the unit and mortar combinations shown in Table 1. Figure 1 shows the fabrication of the bond wrench testing prisms using mortar flows of 125 +- 5 and a jig. Five prisms were fabricated for each mortar batch. In addition, each mortar batch was tested for flow before and after the prisms were fabricated using the procedures shown in ASTM C 780 Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry. Three compression cubes were also fabricated for each mortar batch as per ASTM C 780 [1].

A total of five, face shell bedded, four high stack bonded prisms were fabricated using mortar batched to flows of 125 +- 5 and a jig for each of the unit and mortar combinations shown in Table 1. Two or three prisms were fabricated from a single batch of mortar and mortar flows were taken at the start and at the end of the fabrication, as per ASTM C 780. Mortar compression cube specimens were also formed for each mortar batch and tested for compression as per ASTM C 780. Figure 2 shows these prisms during fabrication.

After bag curing in lab air for 28 days each prism was tested for flexural bond strength. The four high prisms were tested using the procedures described in ASTM E–518. The couplets were tested using the procedures described in ASTM C 1072 Standard Test Method for Measurement of Masonry Flexural Bond Strength [1] and the proposed hollow unit bond wrench testing apparatus Figure 3 shows a prism couplet specimen being tested by the proposed hollow unit bond wrench. Dry stacked block was used to support the specimens and the wrench arm after failure. Note that the upper head was fabricated from aluminum to minimize weight and there was a minimum of 50 mm clearance between the wrench arm and the wood blocks.

Figure 4 shows the four high stack bond prisms in the E-518 testing apparatus before testing. A span of 610 mm (24 in) was used and the top rollers were configured to create point loads at the span third points. The test prisms were seated on the support rollers using a gypsum capping compound that was allowed to harden before testing.

Table 1 - Proposed Test Matrix.

Series	Unit Size	Mortar Type
1	203 mm (8 in)	Type N Masonry Cement
2	203 mm (8 in)	Type N PCL
3	203 mm (8 in)	Type S PCL
4	152 mm (6 in)	Type N Masonry Cement

Note PCL indicates Portland Cement Lime Mortars

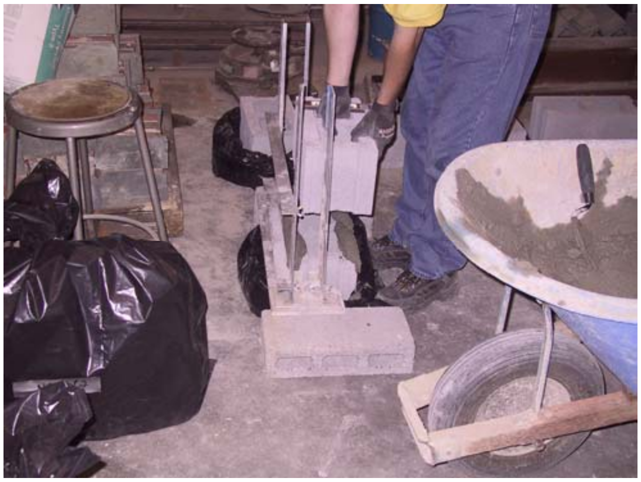

Figure 1 - Lower Block Buttered with Mortar

Figure 2 - Four High Prism Fabrication

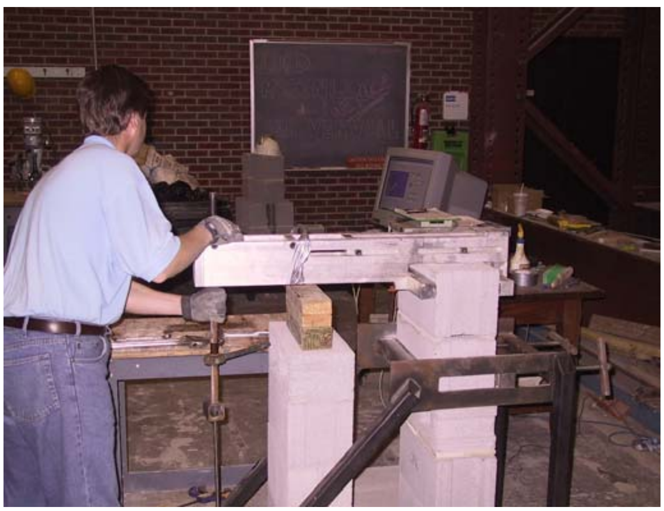

Figure 3 - Proposed Bond Wrench With Couplet Under Test (Note the left stack of blocks and wood were used to catch the arm after failure)

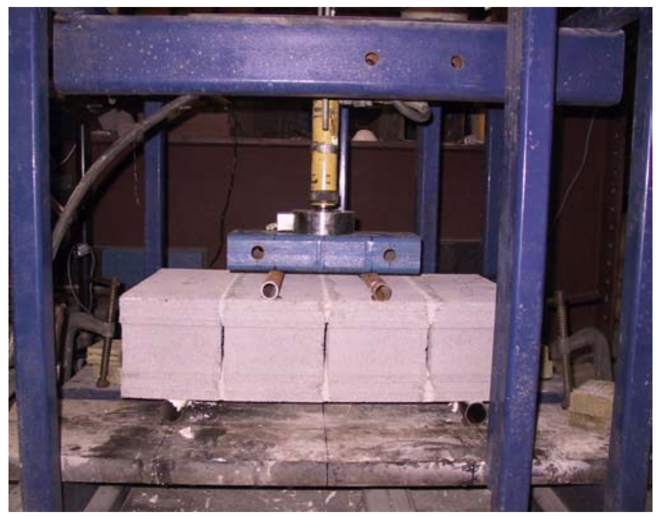

Figure 4 - Four Unit Prism in E 518 Testing Apparatus

TEST RESULTS
The results of the testing program are summarized in the following tables.

Table 2 shows the results of the mortar tests. The cross-sectional properties were measured for each of the couplet and four high block prisms using the procedures in ASTM C 140 Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units [1]. In all cases, the average face shell thickness was assumed to be constant across the width of the block and defined the minimum mortar bedded area. The moment of inertia, area and section modulus were calculated for the minimum net bedded mortared area for both the couplets and 4 high prisms using the procedures described in ASTM Standard C 1072 for hollow units. These values were used to calculate the maximum flexural tensile stress in each prism at failure, again using the procedures described in ASTM Standard C 1072.

The results of the bond wrench tests are summarized in Table 3. At failure, the mortar joint typically separated from the block unit at either the top of the joint (T), or the bottom of the joint (B). In a few cases, the mortar joint separated at both the top and bottom (T/B). In addition, the mortar joints on two couplets fractured as the upper head of the bond wrench was being attached suggesting that the weight of the upper head was sufficient to fail the mortar/block bond. The average and coefficients of variation (COV) for each mortar and unit configuration are also shown in Table 3. It should be noted that the prematurely broken specimens were excluded from this analysis.

Table 2 - Mortar Test Results

Type N Masonry Cement used for Masonry Cement Mortars							**Type S lime Used**			
Type I cement used for PCL Mortars							**Mortar Cube Compression Test Results (MPa)**			
Mix	**Weight Sand (kg)**	**Weight Cement (kg)**	**Weight Lime (kg)**	**Weight Water (kg)**	**Flow Start (%)**	**Flow End (%)**	**A**	**B**	**C**	**Ave.**
PCLS-1 (C1-10)	68.03	21.32	4.54	14.24	124	96	33.8	34.2	31.3	33.1
PCLS-2 (C11-15)	45.35	14.20	3.04	9.66	135	129	27.9	28.2	27.8	28.0
PCLN-1 (C1-5)	33.24	7.12	3.04	7.39	121	113	13.7	14.5	15.2	14.4
PCLN-2 (C6-10)	33.24	7.12	3.04	8.07	123	110	13.5	13.5	12.3	13.1
PCLN-3 (C11-15)	33.24	7.12	3.04	8.07	125	125	12.7	11.6	12.5	12.3
NMAS-1 (C1-5)	33.24	10.57	0.00	6.53	132	132	7.0	7.0	6.7	6.9
NMAS-2 (C6-10)	33.24	10.57	0.00	6.44	128	128	6.4	6.4	6.2	6.3
NMAS-3 (C11-15)	33.24	10.57	0.00	5.90	129	125	7.8	7.1	7.8	7.6
NMAS-4 (6 C1-5)	33.24	10.57	0.00	5.90	129	127	6.9	6.7	7.1	6.9
NMAS-5 (6 C6-10)	33.24	10.57	0.00	6.62	120	110	6.3	6.4	6.3	6.3
NMAS-6 (6 C11-15)	33.24	10.57	0.00	6.76	119	114	6.7	6.3	6.2	6.4
PCLS-3 (P1-3)	34.01	10.66	2.27	8.39	119	101	29.3	28.8	29.5	29.2
PCLS-4 (P4-5)	34.01	10.66	2.27	8.16	127	127	27.0	26.2	28.0	27.1
PCLN-4 (P1-3)	33.24	7.12	3.04	8.30	120	103	11.4	11.3	12.3	11.7
PCLN-5 (P4-5)	33.24	7.12	3.04	8.39	121	121	11.8	12.1	12.4	12.1
NMAS-7 (P1-5)	33.24	10.57	0.00	7.03	132	119	6.4	6.4	6.5	6.4
NMAS-8 (6 P1-5)	33.24	10.57	0.00	7.94	132	113	4.6	5.6	5.1	5.1

Legend - PCL = Portland Cement Lime Mortar – either type S or N, C 1 = Couplet 1
- NMAS = Masonry Cement type N , P 1 = Prism 1

6 C1-5 indicates 150 mm units, couplet 1 through 5 and all the rest used 200 mm units

Table 3 - Couplet Flexural Bond Wrench Test Results

Couplet/Prism ID	Ave. S (I/c) mm^3	Ave. A (mm^2)	Peak Load (kN)	Peak Stress (MPa)	Break Type	Average Stress (MPa)	COV (%)
PCLS-1 C1	1742958	25581	0.176	0.656	T		
PCLS-1C2	1733293	25380	0.175	0.482	T		
PCLS-1C3	1749868	25800	0.178	0.269	B		
PCLS-1C4	1742633	25574	0.176	0.610	B		
PCLS-1C5	1752994	25808	0.178	0.412	T		
PCLS-1C6	1744326	25640	0.177	0.288	T/B		
PCLS-1C7	1757199	25981	0.179	0.256	T		
PCLS-1C8	1741860	25571	0.176	0.085	B		
PCLS-1C9	1748800	25710	0.177		Broke		
PCLS-1C10	1743735	25664	0.177	0.129	B		
PCLS-2C11	1752045	25778	0.178	0.456	T		
PCLS-2C12	1755097	25815	0.178	0.255	T		
PCLS-2C13	1753832	25835	0.178	0.235	T		
PCLS-2C14	1756270	25785	0.178	0.413	B		
PCLS-2C15	1739422	25450	0.175	0.500	T	0.336	51.6
PCLN-1 C1	1755340	25921	0.179	0.560	T/B		
PCLN-1 C2	1748032	25699	0.177	0.170	T		
PCLN-1 C3	1745432	25646	0.177	0.115	T		
PCLN-1 C4	1745738	25784	0.178	0.325	T/B		
PCLN-1 C5	1737876	25557	0.176	0.227	B		
PCLN-2 C6	1756801	25913	0.179	0.252	B		
PCLN-2 C7	1741875	25556	0.176	0.221	B		
PCLN-2 C8	1728853	25510	0.176	0.277	T		
PCLN-2 C9	1748339	25714	0.177	0.347	T		
PCLN-2 C10	1753333	25847	0.178	0.136	T		
PCLN-3 C11	1741650	25638	0.177	0.480	T		
PCLN-3 C12	1738357	25524	0.176	0.436	T		
PCLN-3 C13	1740136	25745	0.178	0.361	T/B		
PCLN-3 C14	1751908	25899	0.179	0.160	B		
PCLN-3 C15	1752755	25868	0.178	0.307	T	0.292	37.9
N MAS-1C1	1746956	25739	0.177	0.120	T		
N MAS-1 C2	1734400	25496	0.176		Broke		
N MAS-1 C3	1742014	25624	0.177	0.085	T		
N MAS-2 C4	1740612	25668	0.177	0.145	T		
N MAS-2C5	1755010	25863	0.178	0.135	T		
N MAS-2 C6	1749951	25752	0.178	0.093	T		
N MAS-2 C7	1740113	25545	0.176	0.083	B		
N MAS-2 C8	1751968	25807	0.178	0.093	T		
N MAS-2 C9	1746544	25650	0.177	0.181	T		
N MAS-2C10	1733088	25488	0.176	0.190	T		
N MAS-3 C11	1742377	25598	0.176	0.117	T		
N MAS-3 C12	1736004	25450	0.175	0.303	T		
N MAS-3 C13	1765752	26140	0.180	0.199	T		
N MAS-3 C14	1750273	25759	0.178	0.099	T/B		
N MAS-3 C15	1744557	25634	0.177	0.150	T	0.133	53.8

Table 3 (cont.) - Couplet Flexural Bond Wrench Test Results

Couplet/Prism ID	Ave. S (I/c) mm^3	Ave. A (mm^2)	Peak Load (kN)	Peak Stress (MPa)	Break Type	Average Stress (MPa)	COV (%)
6NMAS-1 C1	1024000	21386	0.147	0.296	T		
6NMAS-1 C2	1026769	21470	0.148	0.301	T		
6NMAS-1 C3	1031396	21607	0.149	0.451	T/B		
6NMAS-1 C4	1033600	21458	0.148	0.248	T		
6NMAS-1 C5	1033657	21631	0.149	0.300	T		
6NMAS-2 C6	1025952	21483	0.148	0.317	T/B		
6NMAS-2 C7	1031130	21613	0.149	0.165	T		
6NMAS-2 C8	1033101	21693	0.150	0.257	T/B		
6NMAS-2 C9	1023554	21354	0.147	0.101	B		
6NMAS-2 C10	1035149	21709	0.150	0.298	T/B		
6NMAS-3 C11	1040652	21939	0.151	0.253	T		
6NMAS-3 C12	1029496	21522	0.148	0.194	T/B		
6NMAS-3 C13	1027549	21515	0.148	0.104	B		
6NMAS-3 C14	1040908	21965	0.151	0.429	T		
6NMAS-3 C15	1027993	21523	0.148	0.227	T	0.263	39.1

Table 4 shows the flexural tensile bond strength test results for each E 518 test specimen. Also shown are the average and COV for the five identical tests for each mortar and unit configuration evaluated during this investigation. Note that one of the test specimens broke during placement in the testing apparatus and two of the specimens broke at mortar joints, outside of the central maximum moment region, and were discarded in subsequent analysis as directed by the procedures in E 518.

Table 4 - Maximum Flexural Tensile Bond Test Results for the E 518 tests

Couplet/Prism ID	Ave. S (I/c) mm^3	Ave. A (mm^2)	Peak Load (kN)	Peak Stress (MPa)	Average Stress (MPa)	COV (%)
PCLS-1 P1	1758719	25927	0.179	0.883		
PCLS-1 P2	1767285	26145	0.180	1.146		
PCLS-1 P3	1753999	25855	0.178	0.281		
PCLS-1 P4	1749877	25735	0.177	0.522		
PCLS-1 P5	1754946	25846	0.178	0.650	0.696	47.8
PCLN-1 P1	1747909	25704	0.177	0.683		
PCLN-1 P2	1764241	26065	0.180	0.627		
PCLN-1 P3	1760376	25982	0.179	0.000		
PCLN-1 P4	1757041	25911	0.179	0.592		
PCLN-1 P5	1749198	25901	0.179	0.624	0.632	6.0
NMAS-1 P1	1746830	25744	0.177	0.271		
NMAS-1 P2	1764310	25966	0.179	0.371		
NMAS-1 P3	1755865	25883	0.178	0.376	Broke outside load region	
NMAS-1 P4	1753352	25801	0.178	0.292		
NMAS-1 P5	1748489	25695	0.177	0.176	0.299	31.7
6NMAS-1 P1	1023231	21382	0.147	0.408		
6NMAS-1 P2	1027806	21580	0.149	0.387		
6NMAS-1 P3	1033338	21726	0.150	0.296	Broke outside load region	
6NMAS-1 P4	1029304	21653	0.149	0.447		
6NMAS-1 P5	1024787	21430	0.148	0.478	0.403	17.3

DISCUSSION

Examination of Table 3 and Table 4 clearly shows that the flexural tensile bond strengths measured using the proposed bond wrench testing apparatus are lower than those measured for similar specimens tested using the E 518 procedures. These tables also show that the bond wrench test results have slightly higher coefficients of variation than those measured for the E 518 test procedures and both sets of coefficients of variation are relatively high for lab tests. Further, the 150 mm hollow concrete masonry units appear to produce higher flexural strengths and lower coefficients of variation than for 200 mm units. For the 200 mm CMU units, the ratio of flexural bond strengths measured by the E 518 method to that measured by the bond wrench method varies from 2.07 to 2.25. This ratio decreases to 1.6 for the flexural bond strengths measured for the 150 mm CMU specimens.

In effort to determine why these differences occurred, a review of work by others was conducted including a report by R. Thomas [2] that outlined the results of an extensive investigation conducted at the National Concrete Masonry Association (NCMA) Lab. This investigation evaluated the relationship between the flexural strength measured by a "bond wrench" testing apparatus and that produced by large wall tests conducted using the procedures in ASTM E 72. In these tests, it was found that ten identical 1.2 m x 2.4 m x 200 mm CMU (4 ft x 8 ft- 8 in. – type S – PCL Mortar) ASTM E 72 wall tests produced an average flexural bond strength of 1.117 MPa (COV - 32%) and thirty companion, two high prisms tested using a "bond wrench" produced an average 1.165 MPa flexural bond strength (COV - 33%). These results are quite similar and suggest that the bond wrench gives similar results to full sized wall tests. Reasonably good agreement was also found for 100 mm and 300 mm unit specimens, although the 100 mm specimens appeared to give higher bond strength results (similar to the higher strengths found for the 150 mm prisms evaluated in the current investigation). The flexural bond strengths measured in the current investigation (0.336 MPa for the bond wrench and 0.696 MPa for the E 518 tests), for the same mortar type and unit size (PCL Type S – 200 mm units) were significantly lower that the NCMA test values listed above.

The NCMA investigation also evaluated a variety of specimen curing conditions and their affect on measured bond strengths. The NCMA specimen curing conditions that gave the good agreement described above involved spraying the face of the specimens after 24 hours with water until water was observed to flow down the face of the specimen. Immediately after the specimen was sprayed, the bag in which the specimen was constructed was sealed to prevent moisture from escaping. The bags were stripped two days prior to testing. Other bond wrench tests were also conducted using lab air curing with multiple water sprays (no bags), lab air curing (no bags) and curing in outdoor conditions. The results of these tests showed similar results for lab air curing with multiple water sprays and the saturated bag cure. However, the lab air cured specimens (no bags) and specimens cured outdoors produced average bond strengths of 0.317 MPa (COV 64%) and 0.275 MPa (COV 72%), respectively. These values are much lower than the saturated bag cure results, showing curing conditions can have a significant effect on the average bond strengths.

In an experimental comparison of bond strengths measured by different test methods, Hamid and Hakam [3] showed good agreement between bond wrench tests of grouted 200 mm concrete masonry prisms and grouted full scale walls tested using the procedures in ASTM E 72.

Another investigation conducted by Matthys [4] at the University of Texas at Arlington measured the flexural bond strength of full scale 1.2 m x 2.4 m walls (tested using ASTM E 72 procedures), individually built stack bonded prisms, and running bond prisms cut from the full scale walls (tested using a "bond wrench"). All these specimens were constructed with hollow 200 x 200 x 400 mm units, type S PCL or type S Masonry Cement mortar. All nine of the stack bond prisms were 3 units high and all the specimens (walls and prisms) were cured in lab air. For the type S PCL mortar specimens, the average flexural strength measured by the bond wrench on the stack bonded prisms was 0.165 MPa (COV 61.6%), 0.293 MPa (COV 26.7 %) for the full sized wall tests and 0.310 MPa (COV 41 %) for the running bond prisms cut from the wall. The ratio of wall test strength to stack bond prism strength was about 1.8 for the specimens constructed with type S PCL Mortar.

Another investigation conducted at the Construction Technology Laboratory by the Portland Cement Association [5] also looked at flexural bond strengths measured with both clay and hollow concrete masonry units for a number of mortar types using both ASTM C 1072 and E 518 testing procedures. This investigation observed an average flexural strength of 0.627 MPa for 200 mm hollow block (type S – PCL Mortar) prisms tested according to ASTM E 518 procedures and using a "bagged" cure. This compares well with the 0.696 MPa measured during this investigation.

Examination of the bond wrench apparatus used in each of the various investigations shows similar devices were used. The bond wrenches used in the NCMA investigation and in the current investigation are quite similar. Both clamped about ½ the top and bottom block units using either angles or plates over the full width of the units. In addition both bond wrenches had approximately the same lever arm (762 mm and 724 mm, respectively), and applied approximately the same percentage of axial stress to flexural stress (~11%) to the prism mortar joints.

Further a comparison of the bond wrench and the E 518 test procedures suggest that all these tests are applying similar peak flexural stress distributions in low to zero shear stress regimes. Theoretically, they should produce similar results even with the small amount of axial stress present in the bond wrench tests. There appears be something else affecting the bond on the bond wrench couplet prisms since average strengths measured by the proposed bond wrench testing apparatus are much lower than the E 518 tests.

As was discussed previously, specimen fabrication and curing procedures can significantly affect the measured bond. This has been found by a number of investigations and is acknowledged by Note 4 in ASTM C 1072 which reads as follows;

"Workmanship during fabrication, temperature of the materials during fabrication, curing conditions, time between removal from moist curing to test, and other factors may affect the bond strengths measured by this test. Standardized specimen fabrication and curing procedures that attempt to control these variables are prescribed in Test Methods C 1357."

This suggests that the fabrication procedures may be affecting the measured results and is consistent with the findings of the other investigations. In fact, examination of the prism fabrication procedures used in this investigation with respect to those used by others result in the following observations:

1. Both this investigation and the NCMA [2] investigation used prism couplets cured in a bag but the NCMA investigation saturated the prism couplets 24 hours after construction and then bagged the specimens. The NCMA prisms also had tooled joints whereas the current investigation used struck joints.

2. The average flexural tensile bond strengths (0.336 MPa) measured by the proposed bond wrench apparatus is close to the value measured during the NCMA tests (0.317 MPa) for air cured specimens [2]. These values are much lower than the average flexural bond strength of 1.165 MPa measured for specimens that were wetted then bag cured [2]. Lower bond strengths were also measured for the air cured tests at UT Arlington (0.165 MPa) [4]. Bag curing only prevents evaporation and may not ensure that there is sufficient water to fully hydrate the cement in the mortar, especially if the units are dry. Additional moisture may need to be provided to ensure full hydration of mortar joints with the large hollow CMU units. Lack of sufficient moisture may not only have lowered average strengths but may also have increased the variability of the tests.

3. The higher strength of the prisms constructed from the smaller units may also, in part, be a result of less moisture being drawn away from the joints when smaller units are used.

4. Specimens with more joints appear to have higher bond strengths than those with fewer joints with the same curing conditions [6]. This is likely caused by the additional consolidation provided to the central joints in the taller specimens when the upper units are added and may be one the causes for the higher test values for the ASTM E 518 four high prism observed during this investigation. The use of tooled joints for both of these prisms may reduce some of this difference by consolidating all joints a certain amount. Further study of this effect is needed.

5. The ASTM E 518 procedures only test the central joint mortar joint bond that may be stronger that the rest of the joints based on the additional consolidation discussed above.

The proposed bond wrench may be providing lower that expected flexural bond strength results due to the actions described above. Additional testing to determine whether this is the case should be conducted. These tests should be done using prism curing that includes saturated units, joint tooling and flexural bond wrench specimens that are also four units high.

CONCLUSIONS

Based on the results of this pilot test program the following conclusions can be made:

1. The flexural tensile bond strengths measured using the bond wrench testing apparatus are lower than those measured for similar specimens tested using the ASTM E 518 procedures. The bond wrench test values appear to be about ½ those measured by the E 518 tests.
2. The bond wrench test results have higher coefficients of variation than the ASTM E 518 test procedures.

3. The 150 mm (6in.) hollow concrete masonry specimens appear to produce higher flexural strengths and lower coefficients of variation than for those made with 200 mm (8 in) units.
4. The observed differences between the flexural bond strengths measured by the proposed bond wrench testing apparatus and that using the ASTM E 518 procedures may be due to differences in curing procedures and specimen size. Simply reducing evaporation of water through the use of bag curing may not ensure sufficient water is present to allow full hydration of the cement in the mortar. Additional moisture may need to be provided to ensure full hydration of the mortar with the larger hollow CMU units. Further study of this effect is needed.
5. The use of non-tooled joints and the consolidation of lower mortar joints for large hollow unit prisms may affect the measured flexural bond and needs further study.

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