International Building Lime Symposium 2005
Orlando, Florida, March 9 -11, 2005

THE EFFECTS OF AIR-ENTRAINED LIME ON CEMENT-LIME MORTARS*

W. Mark McGinley[1]

Abstract

This research evaluates the effect of air-entrained lime (Type SA) on the properties of cement/lime mortars. Tests comparing cement/lime and cement/air-entrained lime mortars showed no significant differences in water retention and flexural bond strength of mortar when combined with standard concrete masonry units. Although higher air contents appeared to have some effect on the compressive strength of the mortars, the cement/air-entrained lime mortars evaluated in the investigation met the property specifications of ASTM C 270 for air contents up to 10%.

Keywords

Mortar, air-entrained lime, flexural bond, compressive strength, air content, cement/lime mortar

---

[1] Professor, Civil, Architectural, Agricultural and Environmental Engineering, North Carolina A & T State University, Greensboro, NC, 27411, mcginley@ncat.edu

1 Introduction

Currently, the Masonry Joint Standards Committee (MSJC) “Building Code Requirements for Masonry Structures” [MSJC, 2002] designates different masonry assembly flexural tensile strengths for air-entrained cement/lime mortars and non-air-entrained cement/lime mortars. The research reported herein evaluated the effect of air-entrained lime (Type SA) on the physical properties of cement/lime mortars. Specifically, this study investigated the effect of air-entrainment on bond strength and some of the key mortar property requirements defined in the American Society for Testing and Materials (ASTM) Designation C 270 Standard Specification for Mortar for Unit Masonry. Type S cement/lime mortars with and without air-entrainment were evaluated. Because they form the basis of mortar cement qualification requirements and to reduce the number of variables, only standard concrete masonry units were used.

2 Testing program

2.1 Materials

The testing program included a total of twelve different cement/lime mortar mixes, using four lime products and three cement products. All binder materials were provided by the National Lime Association Building Lime Group.

Type S hydrated lime, meeting the specifications of ASTM Designation C 207 Standard Specification for Hydrated Lime for Masonry Purposes, was obtained from two different manufacturers (designated as LS1 and LS2).

Air-Entrained hydrated lime was also obtained from two different manufacturers (designated LSA1 and LSA2). Although both products contained air-entrainment, only one sample, LSA1, met the requirements of ASTM C 207, Type SA.

Portland cement, meeting the requirements of ASTM Designation C 150 Specification for Portland Cement, was obtained from three different manufacturers (designated C-1, C-2, and C-3).

Aggregate – a blend of an equal mass of graded standard (Ottawa) sand and 20-30 µm sand conforming to ASTM Designation C 778 Standard Specification for Standard Sand was used.

Masonry units – Standard concrete masonry units, as described in ASTM Designation C 1357 Standard Methods for Evaluating Masonry Bond Strength - Annex A1, were obtained from the National Concrete Masonry Association.

2.2 Mortar batching procedures and mix configuration

The cement, sand, and lime were combined as shown in Table 1. Each of the 12 unique mortar mixes was batched to meet the Type S proportion requirements of ASTM C 270, as shown in Table 2. The mix volumes were determined using standard unit weights and proportioning constituents by weight. Different amounts of water were added to achieve either a mortar flow of 110 $\pm$ 5 for ASTM C 270 property requirement (compressive strength, water retention, and air content) testing or a flow of 125 $\pm$ 5 for bond wrench prism fabrication and testing. The final mix quantities for each batch are shown in Table 3.

All mortar batches were mixed in a paddle-type (Hobart) mixer using the mixing procedures described in ASTM Designation C 305 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency, except the hydrated lime was added to the mixer at the same time as the cement and water.

Table 1 Mortar Mix (Cement/Lime) Combinations

Component	Lime - S1	Lime - S2	Lime SA1	Lime SA2
C1 – Cement	LS1	LS2	LSA1	LSA2
C2 – Cement	LS1	LS2	LSA1	LSA2
C3 – Cement	LS1	LS2	LSA1	LSA2

Table 2 Cement/Lime Mortar Mix Design (Proportions)

Component	Parts By Volume	Batch Weight (g)
Cement	1	376
Hydrated Lime, Type S or SA	½	80
Blended Sand (dried)	4 ½	1,440

Table 3 Final Mortar Mix Proportions

CEMENT TYPE	LIME TYPE	MASS 20-30 SAND (g)	MASS OTTAWA SAND (g)	MASS CEMENT (g)	MASS LIME (g)	WATER 110 FLOW (mL)	WATER 125 FLOW (mL)
C1	LS1	720	720	376	80	275	295
	LS2	720	720	376	80	290	310
	LSA1	720	720	376	80	265	285
	LSA2	720	720	376	80	280	300
C2	LS1	720	720	376	80	275	295
	LS2	720	720	376	80	290	310
	LSA1	720	720	376	80	265	285
	LSA2	720	720	376	80	280	300
C3	LS1	720	720	376	80	275	295
	LS2	720	720	376	80	290	310
	LSA1	720	720	376	80	265	285
	LSA2	720	720	376	80	280	300

2.3 Specimen fabrication and component tests

For a representative sample of units used for bond wrench testing, two masonry unit properties were determined: the initial rate of absorption (IRA) (using ASTM Designation C 67 Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile procedures) and the dry density (using ASTM Designation C 140 Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units procedures).

The compression strength, air content, water retention, and consistency of the plastic mortar were measured for each of the twelve mortar mixes. Compression tests were conducted using the method described in ASTM Designation C 109/109M Test Method for Compressive Strength of Hydraulic Cement Mortars, and 2-in. (50-mm) cube specimens were used. For each mortar type, six compressive strength cubes were made using the wet curing procedures in ASTM C 109. Three cubes were tested at 7 days and three were tested at 28 days after cube manufacture. The air content of the mortar was measured by the methods described in ASTM Designation C 110 Standard Test Method for Physical Testing of Quicklime, Hydrated Lime, and Limestone for cement/lime mortar Type S (test Section 13). Water retention of each mortar configuration at 110 ± 5 flow was measured by the methods described in ASTM C 110, Section 10. Two replicate tests were performed on separate mortar batches.

To evaluate consistency, initial cone penetration was measured for each mortar configuration using the procedures in ASTM Designation C 780 Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry. This test was run on each of the mortar batches used to fabricate the prisms for bond testing--once prior to starting prism fabrication and once at the end of prism fabrication. No mortar was used more than 30 minutes after mixing. As part of the fabrication procedures, mortar was discarded if the cone penetration fell below 80% of the original value. The results of these tests are not reported in this document.

For each mortar type, six prisms with five mortar joints each were prepared in accordance with Annex A1 of ASTM Designation C 1329 Standard Specification for Mortar Cement. All prisms were constructed by the same person utilizing a prism fabrication jig, mortar form, and drop hammer, as shown in Figures 1 and 2. The mortar used to fabricate the prism was mixed to 125 $\pm$5 flow and three mortar batches were used to fabricate each set of prisms; one batch per two prisms. Each prism was cured for 28 days. All prisms were sealed in plastic bags until one day prior to bond wrench testing, when the bags were removed. All prisms were stored at 24 $\pm$ 9 ^{o}C.

Figure 1 Prism Fabrication Using Jig and Mortar Form

Figure 2 Prism Fabrication Applying Drop Hammer to Consolidate the Mortar Joint

After curing, the flexural bond strength of each mortar joint was determined using the procedures in ASTM Designation C 1072 Standard Test Method for Measurement of Masonry Flexural Bond Strength. Figure 3 shows a prism in the testing apparatus.

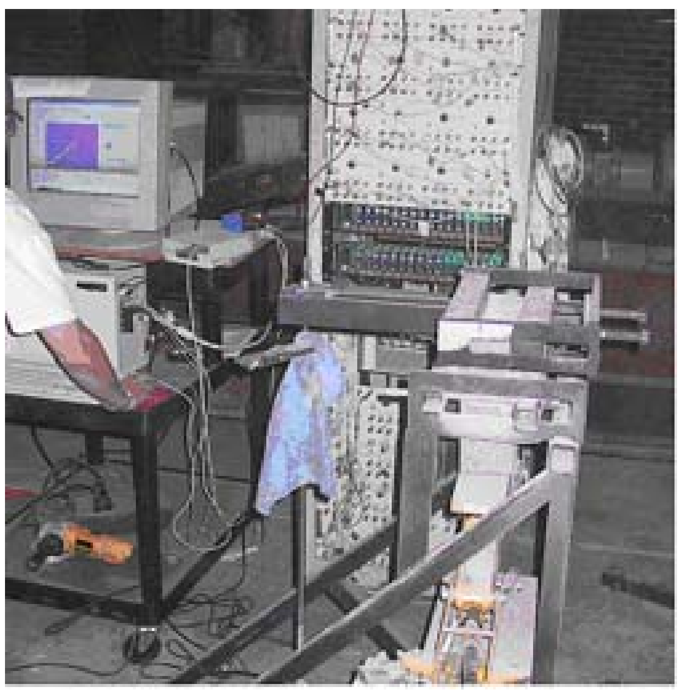

Figure 3 A Prism in the Bond Wrench Testing Apparatus

3 Test results

The average dry unit weight of the concrete masonry units was 128.9 lb/ft^3, with a coefficient of variation (COV) of 0.43%. This value is within the 125 to 135 lb/ft^3 range required for standard masonry units by ASTM Designation C 1357 Standard Test Methods for Evaluating Masonry Bond

Strength. In addition, the average oven-dry IRA of the units was 123.6 g/30in^2/minute, with a COV of 19.9%.

Table 4 presents the average results of the three ASTM C 109/109M flow tests for each of the twelve mortar test types. The average flows varied from 126 to 130, with COVs less than 4%.

The air content for each of the twelve mortar mixes are also shown in Table 4. Each individual value represents an average of three air content tests performed on separate mortar batches mixed with identical amounts of water, cement, lime and sand. Of note is the finding that the mortars made with LSA2 lime did not meet the minimum 7% air content requirement defined in ASTM C 207 for Type SA mortars.

Table 4 also lists the results of the mortar cube compression tests at both 7-days and 28-days. Only average values and COVs for each mortar batch are listed due to space restrictions. These values show a significant increase in strength for all mixes from 7 to 28 days, and all the values greatly exceed the minimum ASTM C 270 property specification compression strength requirement of 1800 psi for Type S mortar.

Table 4 Plastic Mortar Test Results for the 110 Flow Mortars

Mix	Ave. Flow (%)	COV (%)	Ave. Air (%)	COV (%)	Water Reten. 1 (%)	Water Reten. 2 (%)	Avg. 7-day Comp. Stress (psi)	COV (%)	Avg. 28-day Comp. Stress (psi)	COV (%)
LS1 C1	113	2.85	4.30	4.95	87.8	90.4	4,131	2.0	4,364	3.4
LS1 C2	111	1.80	2.79	13.43	90.1	87.6	3,591	1.1	4,205	6.1
LS1 C3	113	2.55	2.67	2.69	98.6	84.3	3,464	3.6	4,268	1.5
LS2 C1	112	2.74	3.33	3.24	92.8	91.3	3,108	1.6	3,625	4.5
LS2 C2	109	0.92	3.21	3.05	89.9	89.1	3,062	8.4	3,612	6.4
LS2 C3	113	1.77	3.05	2.10	90.3	87.8	2,989	3.8	3,522	3.0
LSA1 C1	114	0.88	8.61	1.85	88.6	90.3	2,984	3.9	3,019	0.9
LSA1 C2	110	1.38	7.88	0.72	90.8	88.2	3,124	3.2	3,732	1.9
LSA1 C3	115	0.00	9.43	0.53	93.0	91.3	2,818	7.9	3,039	16.5
LSA2 C1	112	2.36	5.21	3.39	93.8	91.2	3,065	2.9	3,648	1.9
LSA2 C2	112	1.36	5.27	4.08	92.1	91.1	2,879	6.1	3,757	7.0
LSA2 C3	113	1.84	5.18	1.92	89.6	91.2	2,999	5.2	3,917	0.9

COV = coefficient of variation

The results of the flexural bond wrench tests are summarized in Table 5. The average flexural bond stress and COV for each test batch represent the average of 30 mortar joint breaks (6 prisms of five joint tests each). Bond failure was typically observed at the interface of the mortar and the unit, either on the top or bottom of the mortar joint. In some of the tests, the masonry unit failed -- see Figure 4. The flexural strength results of the tests that exhibited brick failure appeared to be consistent with the values obtained by the other tests within the same prism. Further, there was no appreciable difference in the average flexural bond stress and COV values when the test results with unit failures were excluded from the evaluation. Therefore, the failure mode did not affect the bond strength and all test results are included in the tabled values.

Table 5 Flexural Bond Strength Test Results

Mix	Ave. Flexural Bond Stress (psi)	COV (%)	Characteristic Flexural Bond Value (psi)
LS1 C1	106.5	24.5%	73.1
LS1 C2	133.1	22.0	95.7
LS1 C3	132.3	13.6	109.3
LS2 C1	144.6	16.6	113.8
LS2 C2	148.1	19.0	112.1
LS2 C3	148.1	18.8	112.4
LSA1 C1	127.5	16.9	100.0
LSA1 C2	142.0	19.3	107.0
LSA1 C3	121.0	37.9	62.3
LSA2 C1	167.1	15.8	133.3
LSA2 C2	135.3	13.6	111.7
LSA2 C3	129.8	22.5	92.4

Figure 4 Brick Pull-away Failure (Prism 1, C3-LS1, Joint 5)

4 Discussion

The twelve mortar mixes studied met not only the proportion specifications for Type S mortar, as defined in ASTM C 270, but also met the property specifications defined therein. As is typical for cement/lime mortars mixed to the ASTM C 270 proportion specification, all tested mortars had measured compression strengths well in excess of the minimum 1800 psi requirement [Melander and

Conway, 1993; Wright et al, 1993; and Robinson and Brown, 1988]. The air contents of the mortars with and without air-entrainment were all below the 12% maximum allowed, and the water retention was well above the minimum defined in the ASTM C270 property table for Type S cement/lime mortar.

As shown in Figure 5, the use of air-entrained lime appeared to slightly reduce 7-day compressive strength values. However, this reduction was not consistently seen in the 28-day strengths. Although a similar result was found in a previous investigation [Wright, et-al, 1993], the low air contents produced by the LSA2 lime appear to be obscuring trend of the results and a better comparison is given in Figure 6. This figure plots the 7-day and 28-day compressive strengths against air content and includes a linear regression fit of the data. The data does show a drop in compressive strength with increasing air content. However, the large degree of scatter and low degree of fit (R^2 value) suggest there are other factors affecting the compressive strengths of the mortar, such as cement properties. Of note is the finding that even the reduced compressive strengths for all the mortars tested still greatly exceed the minimum required in the property specifications of ASTM C 270 for Type S mortar.

Table 4 shows that the use of air-entrained lime increased water retention for some mortars although it decreased water retention for other mortars. The regression in Figure 7 confirms that there is no significant correlation between air content and water retention.

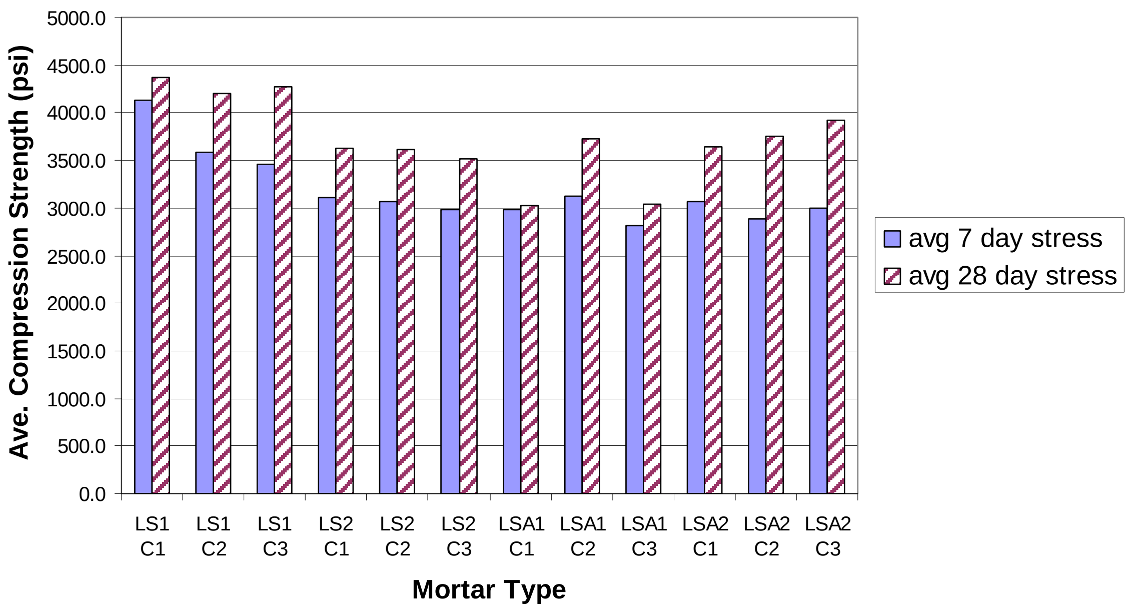

Figure 5: 7 and 28 day Compression Strength Data

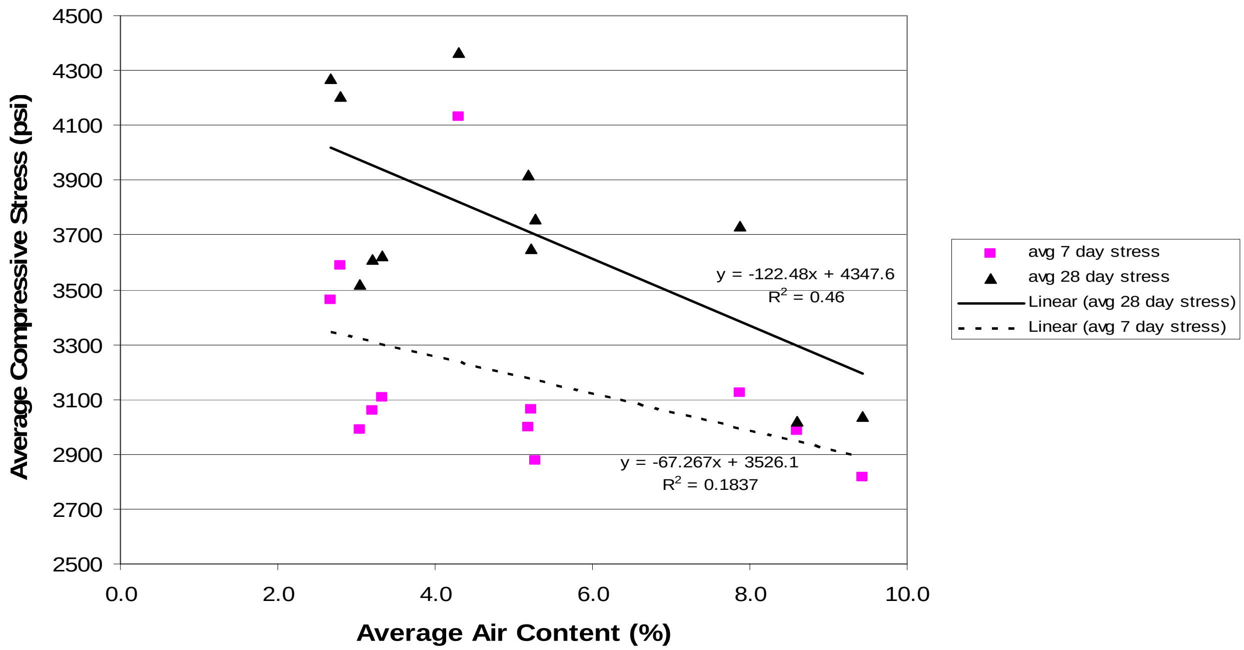

Figure 6 Variation of Compression Strength with Air Content

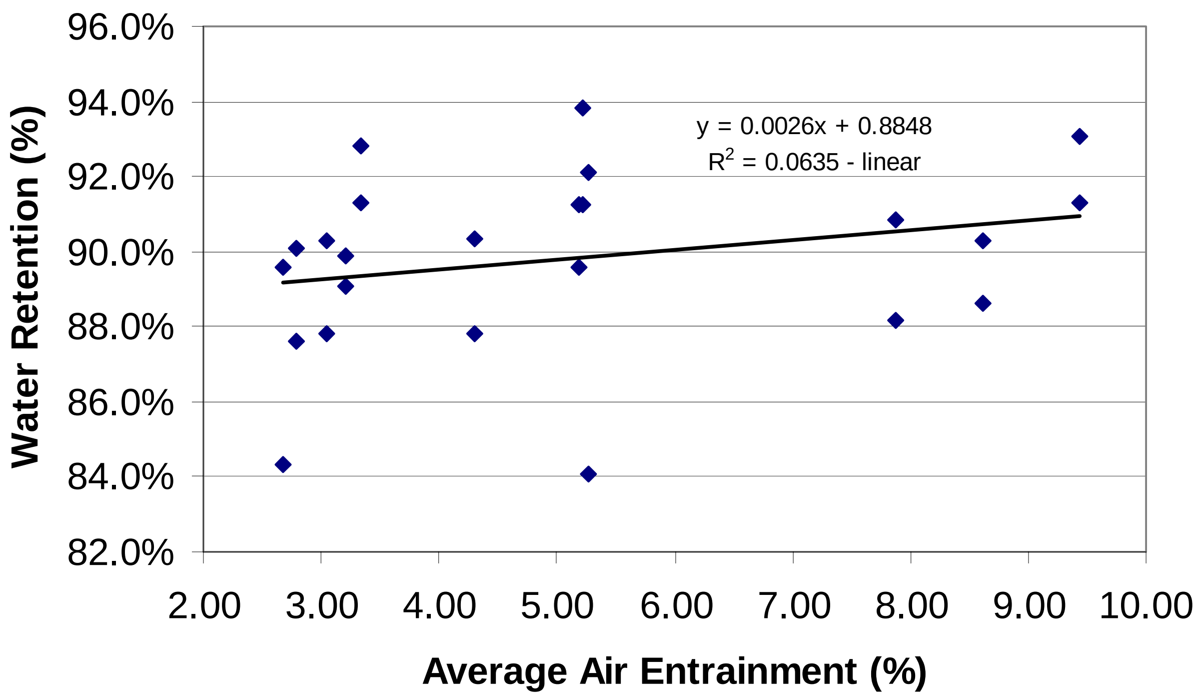

Figure 7 Effect of Air-Entrainment on Water Retention

This investigation also evaluated the effect of air-entrainment (or air content of the mortar) on the flexural bond strength developed between mortars and standard concrete masonry units. Figure 8 shows the variation in flexural bond strengths for the twelve different mortar types. These average flexural strengths varied from 106 to 169 psi, with COVs from 13 to 38%. One of these COVs is relatively high. The high COV may have been caused by low bond results from a single mortar batch (Prisms 5 and 6 of C3-LSA1), which do not appear to be consistent with the results from batches used to make Prisms 1 through 4. Figure 8 and Table 5 show no consistent significant difference in bond strength between the cement/Type S lime and cement/Type SA lime mortars tested.

The characteristic values of bond strength ranged from a minimum of 62 psi to a maximum of 133 psi, where the characteristic value equals the mean minus the product of 1.28 and the standard deviation in accordance with ASTM C 1357. The MSJC Code lists a modulus of rupture value of 100 psi for solid units loaded perpendicular to the bed joints in combination with cement/lime mortars [MSJC, 2002]. Of the twelve mortar samples, two air-entrained and two non-air-entrained cement/lime mortars produced characteristic values that were below the 100 psi value. Though average stresses were above the 100 psi level in each case, the standard deviations for the samples with low characteristic values were high (26.05 psi to 48.85 psi). However, removal of the suspect flexural bond strength values (from Prisms 5 and 6 of C3-LSA1) discussed earlier, would increase the lowest characteristic value of this set of prisms from 62 psi to 113 psi. This revision would also narrow the characteristic value range to a minimum of 73 psi and a maximum of 133 psi with only one air-entrained lime mortar mix producing characteristic values below 100 psi.

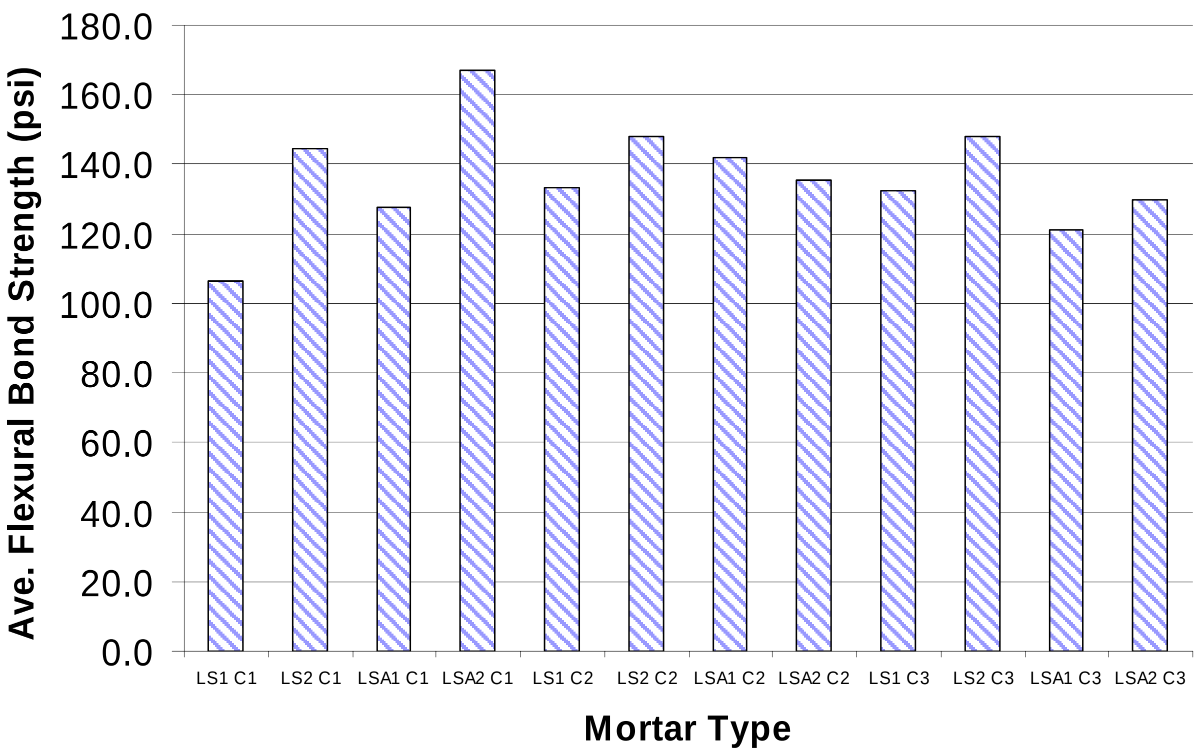

Figure 8 Average Flexural Bond Strengths

Figure 9 shows the average flexural bond strength measured for each mortar mix plotted against measured air content. This figure also shows a linear regression fit of the data. This linear regression has a low slope and a very low degree of fit, suggesting that there is little or no consistent effect of mortar air content on measured flexural bond strength for the air content levels investigated. Others [Robinson and Brown, 1993 and Wright et al, 1993] have shown reduction in bond strength with increasing air contents of cement/lime mortars, and one investigation suggested a mechanism to explain this phenomenon [Lawrence and Cao, 1988]. However, other investigators have found conflicting results, where relatively high air contents produce good flexural bond [Suter et-al, 1998 and Robinson and Brown, 1988]. Most researchers conclude that many factors affect the bond between mortar and masonry units. This study shows that air contents below 10% may not significantly affect the bond between cement/lime mortars and standard concrete masonry units.

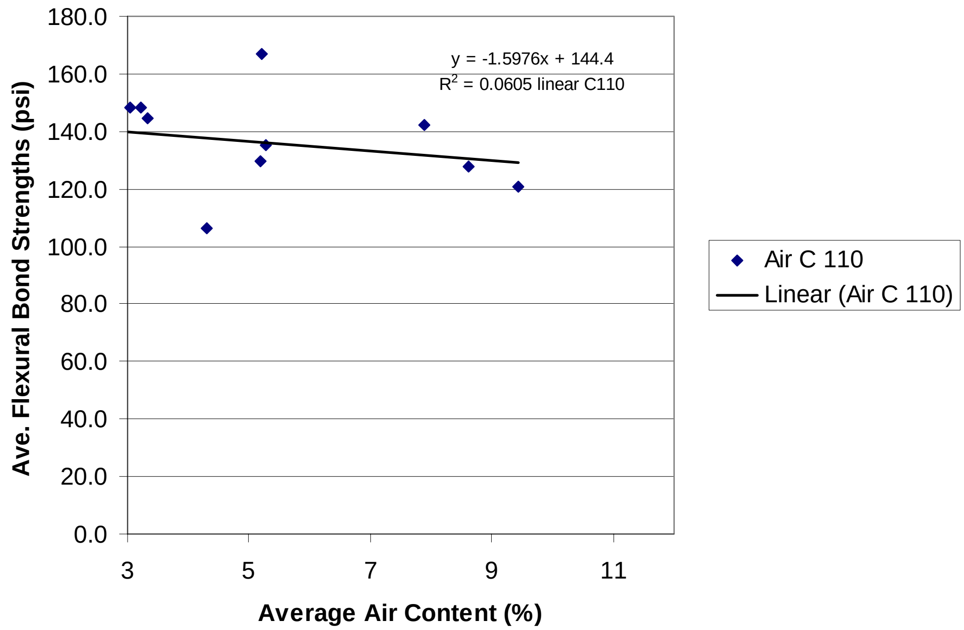

Figure 9 Variation of Flexural Bond Strength with Measured Air Content

The results of this study suggest that the current Masonry Standards Joint Committee Masonry Code (MSJC) provisions that require a reduction in the flexural bond strength of masonry built with air-entrained cement/lime mortar may need to be re-examined [MSJC, 2002]. It appears that using air-entrained lime does not significantly affect the strength of cement/lime mortar mixed according to the proportion specifications of ASTM C 270 when the mortar air content is below 10%. ASTM C 270 imposes an upper limit of 12 % air content in cement/lime mortars where reinforcement is present.

5 Conclusions

Based on twelve different cement/lime mortars and standard concrete masonry unit combinations:

1. All mortars evaluated met both the proportion and property specification requirements for Type S mortar defined in ASTM C 270.

2. The use of Type S or Type SA hydrated lime did not produce any significant consistent effect on mortar water retention or flexural bond strength when tested with standard concrete masonry units at air content levels below 10%. In addition, while increased air content appeared to reduce the compressive strength of cement/lime mortars, this reduction was not large nor did it reduce the strength below acceptable levels.

3. The data suggest that the MSJC provisions requiring a reduction in allowable flexural tensile strength values for air-entrained cement/lime mortars ASTM 270 may need to be re-examined.

6 Acknowledgements

The author would like to gratefully acknowledge the National Lime Association Building Lime Group for their financial support; Margaret Thomson and Michael Tate for their technical assistance; and Scott Singleton, a graduate student at North Carolina A & T State University, for conducting most of the tests described in this report.

7 References

ASTM INTERNATIONAL, 2003, Annual Book of Standards, American Society for Testing and Materials, Philadelphia, Volumes 4.02 and 4.05.

Lawrence S. J. and Cao N. T., 1988, Microstructure of the Interface between Brick and Mortar, Proceedings of the 8th International Brick Block Masonry Conference, University College, Dublin Ireland.

Masonry Standards Joint Committee, 2002, Building Code Requirements for Masonry Structures (ACI 530/ASCE 5/TMS 402), The Masonry Society, Boulder CO.

Melander, J. M. and Conway, J. T., 1993, Compressive Strengths and Bond Strengths of Portland Cement-Lime Mortars, Masonry Design and Construction: Problems and Repair STP 1180, John M. Melander and Lynn R. Lauersdorf, Eds., American Society for Testing and Materials, Philadelphia.

Robinson, G. C., and Brown, R. H., 1988, Inadequacy of Property Specifications in ASTM C 270, Masonry: Materials, Design, Construction and Maintenance STP 992, H. A. Harris Ed., American Society for Testing and Materials, Philadelphia.

Suter, G T., Thomson, M. L.., and Fontaine L., 1998, Mortar Study of Mechanical Properties for Repointing of the Canadian Parliament Buildings , APT Bulletin, The Journal of Preservation Technology, Volume XXIX, No. 2.

Wright, B. T., Wilkins, R. D., and John, G. W., 1993, Variables Affecting the Strength of Masonry Mortars, Masonry Design and Construction: Problems and Repair STP 1180, John M. Melander and Lynn R. Lauersdorf, Eds., American Society for Testing and Materials, Philadelphia.