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COMPARATIVE INVESTIGATION OF BOND PROPERTIES OF PORTLAND CEMENT-LIME MORTARS AND LIME REPLACEMENT MORTARS

Michael P. Schuller, P.E.
Robert S.K. van der Hoeven, E.I.T.
Atkinson-Noland & Associates, Inc.
2619 Spruce Street
Boulder, CO 80302
(303) 444-3620
info@ana-usa.com

Margaret L. Thomson, Ph.D.
Chemical Lime
P.O. Box 127
BMI Complex
Henderson, NV 89015
(702) 565-3833
mthomson@anv.net

A research program was conducted to compare various properties of traditional portland cement-lime mortars with properties of mortars containing lime-replacement additives. One of the objectives of the investigation was to compare the mortar-unit bond strength provided by the different mortar types and to compare the variability in test data obtained using clay brick versus the standard concrete brick required by Uniform Building Code Test Method 21-20.

Brick, block, and mortars were characterized using standard ASTM test methods. In addition, surface roughness of brick and block was measured using a laser profilometer. Bond strength tests were conducted at an age of 28 days, following the requirements of UBC Test Method 21-20. Results indicate that portland cement-lime mortars have greater bond strengths than lime-replacement mortars. Bond strengths of masonry built using the NCMA standard concrete brick were greater and had less within-test variability than companion bond tests conducted using an extruded clay brick.

INTRODUCTION

The strength of bond between mortar and masonry units is important for defining masonry's resistance to lateral flexural and shear loads. Masonry with poor mortar/unit bond is prone to cracking under the application of lateral loads. Cracks permit moisture infiltration, which in turn increases the likelihood for related freeze-thaw damage and, potentially, damage to interior building finishes.

Many projects have investigated the bond strength provided by portland cement-lime and masonry cement mortars using the bond wrench apparatus described in ASTM C 1072, *Test Method for Measurement of Masonry Flexural Bond Strength*, and Uniform Building Code Standard 21-20, *Standard Test Method for Flexural Bond Strength of Mortar Cement*. Previous projects have found bond strength to be related to many factors, including workmanship, mortar proportions, mortar materials, unit absorption, unit suction, and unit surface texture (Mayes, 1975). The purpose of this study was to compare the flexural bond strength provided by different mortar formulations and investigate the necessity for using a standardized concrete masonry unit as required by UBC 21-20. The test program considered seven different mortar formulations. Four portland cement-lime mortars were used, along with 3 additional test series using mortars containing lime-replacement products. All mortars were proportioned to meet requirements for Type S mortar. Bond test specimens were constructed using extruded clay brick and the NCMA standard concrete masonry unit for each mortar type.

MATERIALS

All test specimens were constructed using masonry units and mortar materials obtained from single production runs. All mortar mixing, prism fabrication, and bond testing was conducted by a single operator to minimize the likelihood for any variations which could be attributed to differences in operating procedures

Clay Brick

Clay brick used for prism construction were 100 percent solid extruded units. Brick absorption and strength properties were determined in accordance with ASTM C 67, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*. Results of brick characterization tests are provided in Table 1.

Concrete Brick

A second series of bond test prisms were constructed using 100 percent solid concrete brick, manufactured by the National Concrete Masonry Association (NCMA) to meet the proportion and property requirements described in UBC 21-20. Concrete brick were tested by NCMA; properties are listed in Table 2.

Brick Surface Roughness

Two each of the clay and concrete brick were tested using a laser profilometer to determine the roughness profile of bedded surfaces. The laser profilometer provides a convenient means to measure surface profiles to sub-millimeter accuracy using a nondestructive, non-contact procedure. A description of the laser profilometer and typical usage of the device can be found in Binda, et al. (1996). Two longitudinal and two lateral scans were made on each of the top and bottom bedded surfaces of each brick, for a total of 32 scans. Based upon test results, units used for prism construction can be grouped into three main categories: a) the typical smooth-faced clay brick; b) a non-typical rough-faced clay brick; and c) concrete brick. A set of representative profilometer scans are shown in Figure 1. Note that the smooth brick have typical surface amplitude variations on the order of 0.1 mm, with occasional variations as large as 0.4 mm. Concrete brick surfaces are characterized by many deep depressions on the order of 0.5 to 1.5 mm deep. Rough-faced clay brick, on the other hand, have many small surface variations of about 0.1 mm.

Surface texture can be described using a simple roughness parameter, based upon a procedure described by Lange, et al. (1993).

$$R_L = \frac{\text{actual profile length}}{\text{projected profile length}} \tag{1}$$

The surface roughness parameter R_L is commonly used as a descriptor of relative roughness of cracks and fracture surfaces and is used here to compare the surface roughness of the clay brick with the surface roughness of the concrete brick. Higher roughness values are associated with more tortuous surfaces, whereas a roughness parameter of 1.0 indicates a perfectly smooth surface. Previous investigations on the nature of mortar/unit bond have mentioned that surface porosity and roughness play an important role in defining bond strength (Sise, 1988, and CSA, 1994), but little work has been done to characterize the actual surface roughness and its role in defining mortar/unit bond.

Surface roughness calculations are listed in Table 3. Concrete brick surfaces were fairly consistent, with an average roughness parameter of 1.050. Examination of clay brick data showed there to be two distinct groupings. Twelve of the brick scans were on relatively smooth surfaces, with an average roughness parameter of 1.024. Four of the scans had high roughness values, with an average roughness parameter of 1.162. These brick had many small tears in the brick surface, presumably caused during wire-cutting of the green clay prior to firing. Hence the high surface roughness for this group of brick was caused by many shallow, localized indentations, each being on the order of 0.1 mm deep, rather than the fewer, but deeper, depressions characteristic of the concrete brick. Note also that the coefficient of variation of calculated roughness parameters is substantially greater for the clay brick. Concrete brick appear to provide a more uniform surface roughness based upon the lower coefficient of variation of their calculated roughness parameters.

Mortar

The same portland cement was used for all seven tested mortar formulations. Portland cement meeting the requirements of ASTM C 150, *Standard Specification for Portland Cement* for Type I cement, was obtained directly from the manufacturer. Mortars “A”, “B”, “C”, and “D” used Type S hydrated lime meeting the requirements of ASTM C 207, *Standard Specification for Hydrated Lime for Masonry Purposes.* The four lime materials were produced by four separate production operations. Portland cement and lime were stored in the laboratory in airtight containers.

The three lime-replacement materials represent the three main types currently being produced. Mortar "E" included a pozzolanic lime-replacement; mortar "F" used a proprietary lime-replacement product, and mortar "G" used proprietary resin compounds as the lime-replacement. All three lime-replacement products were provided in dry form and were stored in air-tight containers.

Sand for mortar was obtained in bagged form. Sand gradation met the requirements of ASTM C 144, *Standard Specification for Aggregate for Masonry Mortar.*

All mortars investigated were proportioned to meet ASTM C 270 requirements for Type S mortar. Lime-replacement materials were proportioned according to the manufacturer's recommendations. The water content of each mixture was defined by flow requirements of UBC 21-20 for construction of bond test specimens. Mortar was batched by weight and mixed for 5 minutes in a 1.5 cubic foot vertical paddle mixer. Mix proportions are provided in Table 4. All seven mortar types were characterized to determine properties in both the plastic and hardened states. Additional information on mortar properties can be found in Schuller, et al., (1998).

BOND TESTS

Specimen Construction

Flexural bond strength was determined according to Uniform Building Code Standard 21-20, *Standard Test Method for Flexural Bond Strength of Mortar Cement.* A total of 6 prisms, or a total of 30 joints, were constructed for each mortar and brick type described above. Prisms were constructed in an alignment jig using a drop hammer to seat each unit as described in the test standard. Constructed prisms were bag-cured and tested at an age of 28 days.

Test Results

Specimens were tested using a bond wrench apparatus, as required by UBC 21-20. It is believed that this apparatus was developed in the mid-1980's, as mentioned by Sarker and Brown (1987). Load was applied mechanically by turning a nut on a threaded loading rod. Load magnitude was measured and recorded using an electronic load cell and data acquisition system. Results of bond tests are listed in Table 5 and shown in Figure 2, for each of the seven mortar types, using both clay brick and concrete brick.

Sketches were made of each joint following fracture to define approximate failure surfaces. Three distinct failure types were noted: 1) a clean break along the interface between mortar and unit, with all of the mortar adhered to one unit; 2) an interface fracture with part of the mortar on one unit and the remainder on the other; 3) partial failure through the mortar itself, with mortar adhered to both unit surfaces. Of the clay brick joints tested, 66 percent had a type 1 failure, compared to 58 percent of the concrete brick joints. Twenty-three percent of the clay brick joints and 25 percent of the concrete brick joints had type 2 failures, and 11 percent of the clay brick joints and 17 percent of the concrete brick joints had type 3 failures. In addition, several of the concrete brick joints failed by fracture of the brick itself. Joint failure types indicate that the mortar, in general, adhered better to the concrete brick than the clay brick.

Some joints failed prematurely, during installation in the bond wrench apparatus, and were not included in determination of statistical data. The number of joints tested successfully for each test series are listed in Table 6. Only one test series, lime-replacement mortar type "G" had a significant number of un-tested joints. Six joints, or 25 percent of the total number of joints constructed, could not be tested due to fracture during installation in the test device. This test series also displayed the lowest average bond strength for both the clay brick and concrete brick test series.

DISCUSSION

Test results indicate that, for all cases, portland cement-lime mortars have greater flexural bond strengths than lime-replacement mortars. It is also interesting to note that, in general, the coefficient of variation in test results is greater for the lime-replacement mortars, regardless of whether clay or concrete brick are used.

Concrete brick specimens had greater bond strengths than their clay brick counterparts, except for mortar types F and G, both of which were lime-replacement mortars. With all other factors being equal, this may indicate that these two mortar types lack the ability to flow into the surface depressions in the concrete brick. It was noted that, upon close inspection of the failure surfaces of joints made with mortar types F and G, there appeared to be poor total contact between the mortar and brick. No distinct voids were observed.

The reason for the higher bond strengths for the concrete brick specimens may be due to a number of factors. Concrete brick had greater initial rate of absorption, greater total absorption, and greater surface roughness than the clay brick. All of these parameters are known to affect bond strength. It is also possible that incompletely hydrated cement particles at the concrete brick surface were re-activated due to moisture imparted to the brick from fresh mortar during specimen construction. Hence the greater bond strengths for the concrete brick may be attributed to a combination of increased mechanical interlocking and as well as a possibility for some degree of chemical bonding.

For all test series, the variability in test results, as measured by the coefficient of variation, was less for the concrete brick specimens. Coefficients of variation for the concrete brick test series ranged from 4 to 65 percent less than their clay brick counterparts. On average, the coefficient of variation for concrete brick bond strength was 37 percent less than the coefficient of variation for companion clay brick specimens. This significant and consistent difference indicates that it is important to use the standard concrete brick as specified in UBC standard 21-20 to minimize differences caused by slight unit variations.

All specimens were constructed at the same time, using the same batch of mortar, hence it would appear that within-test variations would be related mainly to variations in the brick used. The variability in test results is puzzling, because the clay brick themselves had lower coefficients of variation for initial rate of absorption, total absorption, and compressive strength. The only characterization test where clay brick had a greater coefficient of variation were the surface profilometer tests.

CONCLUSIONS

Results of tests described herein show there to be the several distinct trends.

1. Flexural bond strength of masonry built using traditional portland cement-lime mortars is greater than bond strength of lime-replacement mortars.
2. Concrete brick specimens had greater bond strengths than clay brick specimens.
3. Bond strengths measured for concrete brick specimens had less within-test variability than bond strengths measured for clay brick specimens.
4. A laser profilometer is a useful tool for characterizing the surface roughness of different brick types. Surface roughness of concrete brick, manufactured to the specifications of UBC 21-20, is more consistent than the surface roughness of extruded clay brick.

An additional task of the research project was to investigate the nature of bond strength development versus time for the seven different mortar formulations. A sufficient number of test specimens were constructed during this research project to conduct bond tests at ages of 60 and 90 days. This work is currently in progress; test results will be reported upon completion of the tests.

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TABLE 1 – Characteristic properties of clay brick units.

	Compressive Strength MPa, (psi) (n=5)	Initial Rate of Absorption $g/m^2/min$ $(g/30in^2/min)$ (n=16)	24-Hour Cold Water Absorption (%) (n=7)	5-Hour Boil Water Absorption (%) (n=7)	Saturation Coefficient (n=7)
Mean	116 (16,800)	925 (17.9)	5.8 %	7.6 %	0.76
Coefficient of Variation	5.2 %	12 %	2.4 %	3.0 %	2.7 %

TABLE 2 – Characteristic properties of concrete brick units.

	Compressive Strength, Mpa (psi) (n=3)	Initial Rate of Absorption, $g/m^2/min$ ($g/30in^2/min$) (n=30)	Cold Water Absorption (%) (n=30)	Density, kg/m^3 (lb/ft^3) (n=30)
Mean	29.1 (4,220)	3,038 (58.8)	8.4	2,095 (130.8)
Coefficient of Variation	9.6 %	16.8 %	4.6 %	0.9 %

TABLE 3 – Surface roughness parameters for clay and concrete brick.

Brick Type	No. of Scans	Surface Roughness, R_L	Coefficient of Variation (%)
Clay	12	1.024	50
Clay	4	1.162	41
Concrete	16	1.050	26

TABLE 4 – Mortar mix proportions.

	Volumetric Mix Proportions			Quantity*	Typical Mix Proportions, By Weight (g)			
Mix	Cement	Lime	Sand	Lime-Replacement	Cement	Lime	Sand	Lime-Replacement
A	1	0.5	4.5	0	13,085	2,720	49,900	0
B	1	0.5	4.5	0	13,085	2,720	49,900	0
C	1	0.5	4.5	0	13,085	2,720	49,900	0
D	1	0.5	4.5	0	13,085	2,720	49,900	0
E	1	0	4.5	1.58 kg (3.5 pounds)	13,085		49,900	486
F	1	0	4.5	14.2 g (0.5 ounces)	13,085		49,900	4.95
G	1	0	4.5	42.5 g (1 ½ ounces)	13,085		49,900	14.0

* Quantity listed is per 42.6 kg (94-pound) bag of portland cement

TABLE 5 – Representative 28-day mortar compressive strengths determined using mortars mixed to the flow requirements of ASTM C 270.

Test Series	Type*	Compressive Strength, MPa (psi)	Coefficient of Variation (%)
A	PCL	23.4 (3400)	2.5
B	PCL	22.2 (3220)	1.3
C	PCL	22.8 (3300)	5.4
D	PCL	27.1 (3930)	9.0
E	LR	18.6 (2700)	2.3
F	LR	15.7 (2280)	5.2
G	LR	16.4 (2380)	1.5

*PCL = portland cement-lime mortar; LR = lime-replacement mortar

TABLE 6 – Results of 28-day bond wrench tests.

Test Series	Type*	Clay Brick			Concrete Brick		
		n	Bond Strength, MPa (psi)	Coefficient of Variation (%)	n	Bond Strength, MPa (psi)	Coefficient of Variation (%)
A	PCL	29	1.16 (168)	34	30	1.50 (218)	21
B	PCL	30	1.07 (155)	26	29	1.66 (241)	25
C	PCL	28	1.04 (151)	40	30	1.67 (242)	14
D	PCL	30	1.28 (186)	28	30	1.54 (224)	16
E	LR	29	0.78 (113)	36	30	1.04 (151)	31
F	LR	28	0.73 (106)	53	28	0.57 (83)	27
G	LR	24	0.60 (87)	43	30	0.43 (63)	24

*PCL = portland cement-lime mortar; LR = lime-replacement mortar

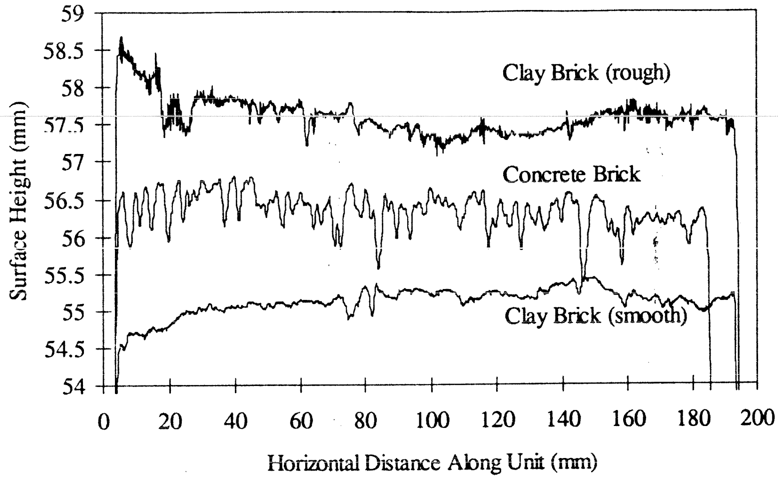

Figure 1. Masonry unit surface roughness was measured using a laser profilometer. A total of 32 separate scans were made; shown are representative surface profiles for a) smooth clay brick; b) rough clay brick; c) concrete brick.

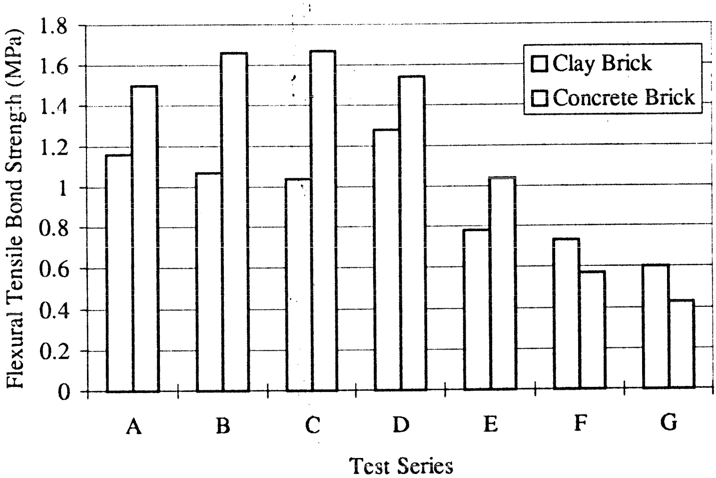

Figure 2. Flexural tensile bond strengths or clay brick and concrete brick test series.