MASONRY INFORMATION

Bond Strength Testing of Masonry

INTRODUCTION

Masonry mortars combined with masonry units form masonry elements that perform a significant role in providing load bearing walls and weather resistive facades. The mortar, consisting of one or more cementitious materials, develops physical properties which are largely dependent on the materials combined. The significance of specific properties depends on the role of the appraiser. The mason desires a workable mortar for ease of placement; this workability characteristic influences the performance of the masonry. The engineer focuses on the ability of the masonry to support compressive loads. For walls resisting out-of-plane loads, the engineer also wants the mortar to develop sufficient bond strength with the units to support flexural tensile stresses incurred. The owner desires masonry with durable characteristics requiring a minimum of maintenance. There is no single mortar that will provide optimum characteristics to all interested parties. Caution should be exercised against selecting a single performance characteristic as being the most important while de-emphasizing the significance of other properties.

Recently, bond of mortars to units has been receiving considerable attention. 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. A chemical and a mechanical bond exist in each category. 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 document focuses on *bond strength* when using the term *bond*.

In service, masonry relies on the bond of mortar to unit to maintain its monolithic integrity under varying exposure conditions. For example, during positive or negative wind loading–wind pressure or suction–the masonry relies on the bond to transfer stresses throughout the entire masonry segment. Because of its significance to performance, bond remains a subject of interest to many designers and researchers. Many efforts have been made and continue to be made to develop improved ways of measuring bond strength directly, or to establish correlation with other more easily measured physical properties.

DEVELOPMENT OF TEST METHODS

Through many past research programs, several different procedures for measuring bond strength have been developed. Some of these have been adopted as ASTM standard test methods.

Early (1932) bond research completed by Anderegg [Ref. 1] involved masonry assemblies tested as simple beams with centerpoint loading. A modulus of rupture (flexural bond strength) of 30 psi was recommended. Later in 1940 and 1942 [Refs. 2 & 3], two-brick assemblies, which were cantilever loaded, were tested as indicated in Figure 1. This method of preparing and testing specimens resulted in higher bond strengths–a minimum bond strength of 50 psi at 28 days was recommended for masonry. The studies illustrate the significance that specimen preparation, conditioning, and testing procedures have on the determination of bond strength.

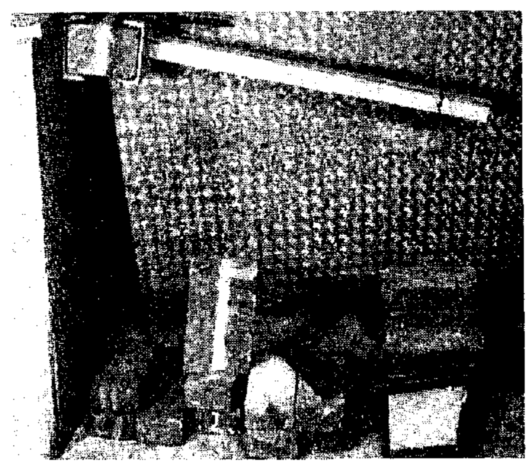


Figure 1—Breaking 2-brick beams in cantilever.

The earliest ASTM standard test method for measuring bond was Test Method C 321, entitled "Standard Test Method for Bond Strength of Chemical Resistant Mortars." Originally published in 1954, this standard provides for masonry assemblies to be prepared and tested, such that the mortar joint separating crossed bricks is subjected to a direct tensile force. To allow testing in a conventional compression testing machine, where downward forces are common, a testing jig is utilized to convert the downward force to tension. Although it was developed to test bond strength of chemical resistant mortars, this "crossed brick couplet" test method has also been used to test specimens fabricated using conventional mortars.

An extensive research program completed by Fishburn [Ref. 4] involved identification of materials, measuring material properties, and researching the correlation between bond strength and wall performance. The "crossed brick couplet" test method was used to correlate the bond strength of mortar to unit with the structural performance of masonry walls. In 1959 ASTM adopted the detailed test procedure used by Fishburn as Test Method E 149. The standard was entitled "Standard Test Method for Bond Strength of Mortar to Masonry Units." This standard addressed the testing of bond strength of mortars to clay/shale units and concrete masonry units. In addition to the "crossed brick couplet" bond test used for brick, concrete masonry assemblies were subjected to eccentric loading, converting the downward force of a compression testing machine to a constant bending moment, with tension on one face of the assembly and compression on the other face of the assembly nearest the imposed load. Originally developed under the jurisdiction of ASTM Committee E-6 on Performance of Building Constructions, this method is now under the jurisdiction of ASTM Committee C-12 on Mortars for Unit Masonry and was redesignated ASTM C 952 in 1981.

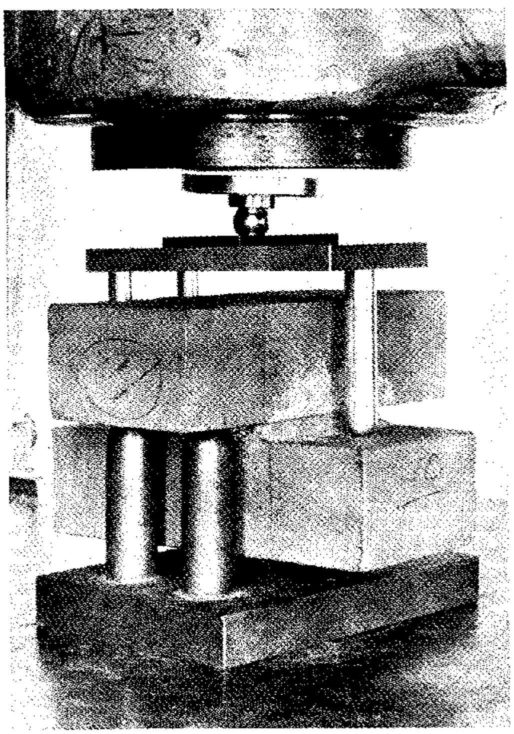


Figure 2—Crossed brick couplet test method – ASTM C 952.

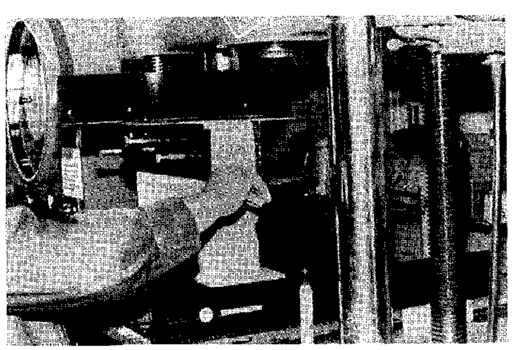


Figure 3—Concrete masonry bond strength test method – ASTM C 952.

In 1974 another bond strength test procedure was adopted by ASTM. This standard, Test Method E 518, entitled "Standard Test Method for Flexural Bond Strength of Masonry," involves fabricating stacked-bond, unit-masonry assemblies. These specimens are tested horizontally as simple beams using either third point loading or uniform loading. The side opposite of the applied load is subjected to tension.

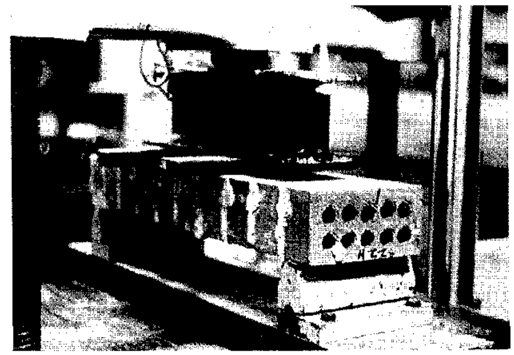


Figure 4—Stacked bond masonry prism tested as a beam – ASTM E 518

More recently (1986) Test Method C 1072, entitled "Standard Method for Measurement of Masonry Flexural Bond Strength," has become popular. In this test, a masonry assembly is subjected to a cantilevered load, which "wrenches" the top brick from the rest of the assembly held beneath in a vise. Again one face of the assembly is subjected to compression and the other to tension.

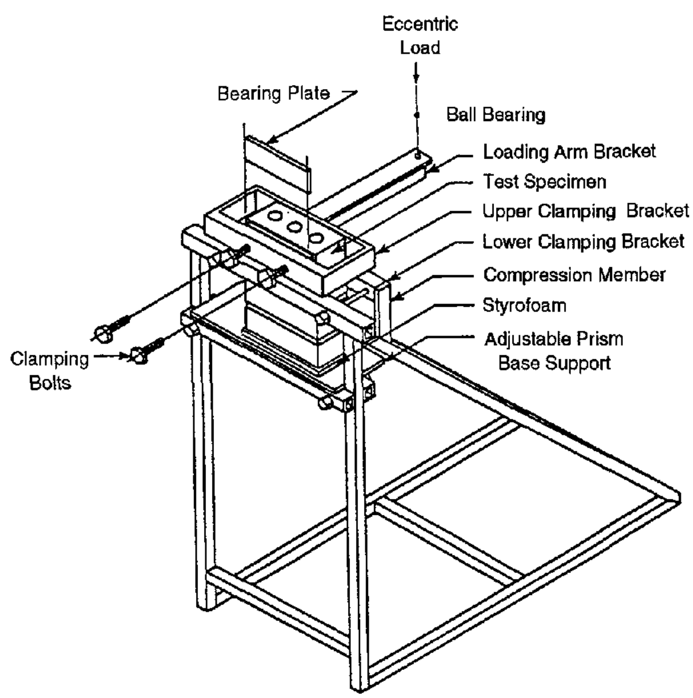


Figure 5—Bond wrench apparatus as depicted in ASTM C 1072

In 1947 ASTM E 72, "Standard Methods of Conducting Strength Tests of Panels for Building Construction," was published as a temporary standard. This standard outlined procedures for measuring the compressive strength, racking strength, and transverse strength of building panels including masonry walls. The procedure for transverse loading of masonry panels involves testing 4-ft wide walls having a height equal to the typical wall height of the building element in use (such as 8 ft). After curing, the wall is subjected to a transverse load until failure, using either a "two point" loading procedure or a uniform loading apparatus (air bag).

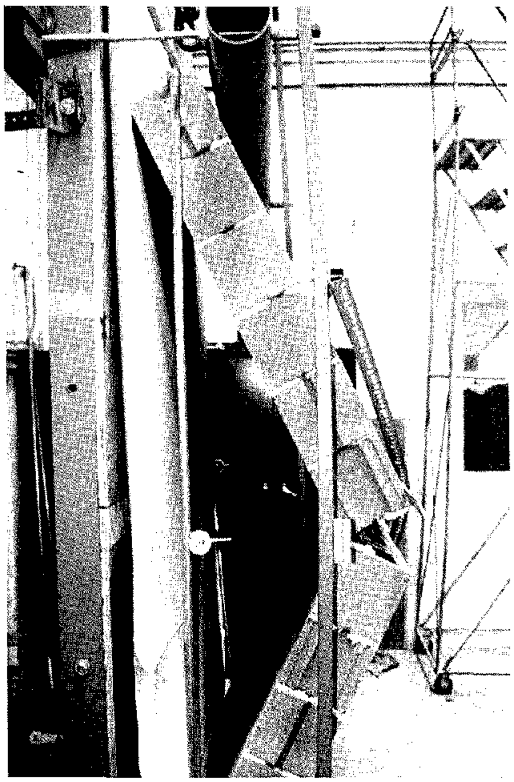


Figure 6—Transverse loading of a masonry wall using the air bag method of ASTM E 72

DISCUSSION OF TEST METHODS

Although each of the above test methods is directed toward measuring the bond between mortar and unit, each approaches the task somewhat differently.

Both ASTM C 321 and C 952 use crossed brick couplet test specimens. This specimen configuration permits direct measurement of the tensile force required to pull the units apart, causing bond failure. Brick units (although seemingly rigid) actually bend when subjected to loading using this testing configuration. Therefore, tensile stresses over the bedded area are not uniform. High stresses are concentrated at the corners. The test specimen corners represent segments of the bedded area most prone to specimen preparation imperfections and early age drying and accompanying shrinkage stresses. Thus, true direct tension is not attained. Since the reported bond strength involves calculating the load uniformly carried by the cross sectional area, effects of the specimen preparation, imperfections in applying uniform loads over the bedded area and non-uniform drying shrinkage stresses influence the measured total load. Additionally, the calculated bond strength is influenced by the modulus of elasticity of the unit involved.

When using the ASTM Test Method C 952 to test concrete masonry, two units are assembled to form a stacked bond prism. The assembly is supported at its base and loaded through a short cantilevered arm, using a conventional compression machine. This setup induces a constant moment, or couple, throughout the masonry assembly. The measured load and calculated bond strength are directly related to the bond strength at the extreme fiber (joint surface) of the assembly. Only two block joined by one mortar joint comprise the specimen. Therefore, failure usually occurs at the top or bottom of the mortar bed joint at its interface with the unit. Exceptions to that mode of failure may be observed if the bond of mortar to unit exceeds the tensile strength of either the unit or the mortar itself. The mechanical principles involved in loading and failure are similar to those of ASTM C1072. However, the short lever arm associated with the ASTM C 952 apparatus produces a high axial stress component in loading, which may affect test results.

ASTM Test Method E 518 masonry assemblies are tested as simple beams using either third point loading or uniform loading. Third point loading provides a constant moment throughout the central third of the test specimen. Failure should occur in this middle third of the specimen. If it does not, test results for that specimen are rejected. The extreme fibers (joint surfaces) are the most highly stressed, and failure occurs at the weakest mortar-to-unit interface. The optional, uniform loading test procedure utilizes an air bag to apply equal pressure distributed over the entire height (length) of the test specimen. Again during loading, failure of the weakest joint occurs at the extreme fibers of the assembly. Only one bond value is obtained per specimen when testing according to ASTM E 518.

ASTM Test Method C 1072 masonry assemblies are tested incrementally, removing the uppermost unit from the course immediately below the joint. Loads applied through a cantilevered arm induce tension over half the mortar joint and compression over the other half. Failure usually occurs at the mortar-to-unit interface. A single six-brick, five-joint assembly permits five bond strength results to be obtained from a single specimen. Brick-sized units of either clay or concrete may be used to prepare the assemblies. This method has probably become more widely used in the United States than the other methods over the past ten years since its adoption as an ASTM test method. That is due largely to the simplicity of the equipment and the fact that each joint of a multi-unit-prism specimen may be tested individually using this procedure. ASTM C 1072 does not currently include testing of assemblies constructed using standard-sized concrete masonry (block) units. (However, research has been performed using such a modified apparatus and revision of the standard to include modifications to the apparatus to accommodate testing of concrete block assemblies would seem imminent.) Tests utilizing standard-sized concrete block are currently performed using ASTM Method C 952.

Since it involves testing specimens approximating the size of masonry element used in construction, transverse strength testing using ASTM Test Method E 72 most closely simulates the performance of a masonry element in service. However, the cost and difficulty associated with such testing make it impractical for most materials evaluation and research testing. Its primary use has been in the development of design criteria for engineered masonry. When testing single-wythe masonry walls, failure generally occurs as a bond failure at the interface of mortar and unit. Some exceptions to that mode of failure may be observed depending on the relative tensile strengths of the materials as compared to the bond strengths achieved between mortar and unit.

It is recognized throughout the testing community that masonry assembly testing does not precisely duplicate construction practices, exposure, and loading. It is more difficult to build assemblies for testing than to build a masonry element. Assembly test procedures generally isolate single joints to measure failure, whereas building elements distribute loads over larger areas. Conditions differ between laboratory or field exposure of assemblies compared to in-place exposure of masonry elements. As a result, variability associated with assembly testing is generally higher than that obtained from wall segment tests such as ASTM E 72. However, correlation between assembly testing and wall segment testing can be established through parallel testing under controlled conditions.

Common among all of the test methods is the desire to measure the force required to cause flexural tension failure at the interface between the mortar and the unit. The results are considered applicable toward establishing the compatibility of materials, a key element for economic structural design of masonry walls. Care must be exercised to select the appropriate test method and then interpret and use the results correctly.

CALCULATING RESULTS

The proper calculation for translating the load at failure to a bond strength result requires an understanding of the formulas involved and some basic engineering. The applicable formulas for the individual test methods are provided in the test procedures. The formulas are based on certain engineering principles which are not explained in the test methods. The following example calculation of bond strength utilizing the C1072 test method illustrates the application of these formulas and engineering principles for a test of specimens constructed using hollow masonry units.

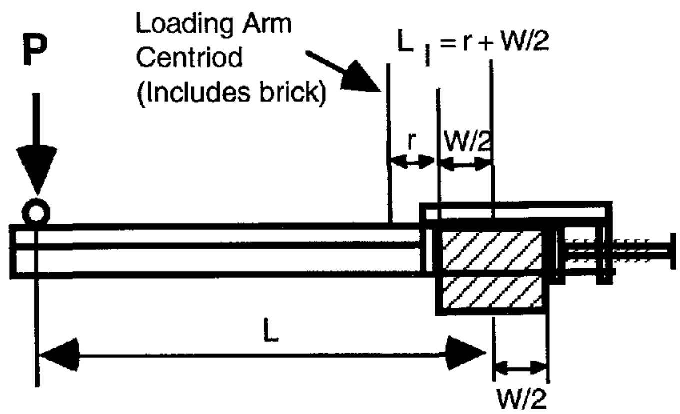
Formula for Flexural Bond Strength - ASTM C 1072

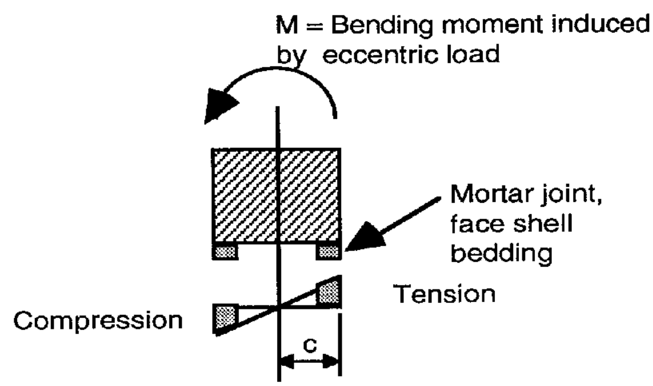
(Hollow Masonry Units)

$$F_n = ((P \times L + P_l \times L_l)/S_n) - ((P+P_l)/A_n)$$

where:

F_n = net area flexural tensile strength, psi (MPa)
P = maximum applied load, lbf (N)
P_l = weight of loading arm and brick unit, lbf (N)
L = distance from center of prism to loading point, in. (mm)
L_l = distance from center of prism to centroid of loading arm (with unit attached), in. (mm)
S_n = section modulus of actual net bedded area, in.^{3} (mm^3)
A_n = net bedded area, in.^{2} (mm^2)



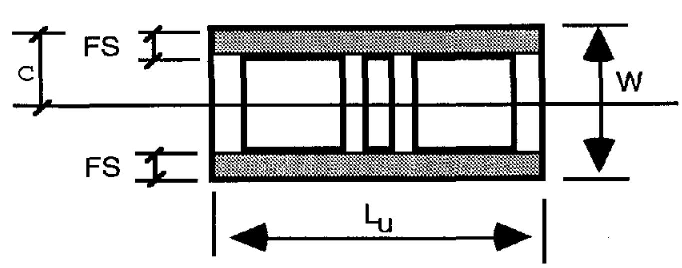


S = I/c

where:
I = moment of inertia of the net bedded area, in.^{4} (mm^4)
c = the distance from the neutral axis (usually the center of the unit) to the extreme tension fiber of the mortar joint (outer edge of unit, in. (mm)

$\mathbf{I_{fs} = [L_u/12][W^3 - (W-2FS)^3]}$, ($I_{fs}$ = moment of inertia for face shell bedding only)
c = W/2
$\mathbf{A = 2(FS)L_u}$

where:
W = width of unit, in. (mm)
r = distance from frame centroid to closest edge of unit, in. (mm)
FS = minimum face shell thickness of unit, in. (mm)
L_u = length of unit, in. (mm)



Let : $P = 140$ lbf, $Pl = 20$ lbf, $W = 4$ in., $L_u = 8$ in., $FS = 0.75$ in., $r = 2$ in., and $L = 24$ in.

Then:

$A = 2(.75)8 = 12$ in.^{2}

$c = 4/2 = 2$ in.

$I = [8/12][4^3 - (4 - 2(.75))^3] = 32.25$ in.^{4}

$S = 32.25/2 = 16.125$ in.^{3}

$L_l = 2 + 4/2 = 4$ in.

$F_n = ((140 \times 24) + (20 \times 4))/16.125) - ((140 + 20)/12) = 213.33 - 13.33 = 200$ psi

EFFECT OF TEST METHODS ON RESULTS

As would be anticipated, the array of test methods previously described produce different measured bond strength results.

Kuenning [Ref. 5] demonstrated the effect of test methods on measured bond strength. Crossed brick couplets tested using the testing jig of ASTM C 952 were compared with like specimens tested in direct tension using metal plates glued to their surface. This study indicated that the cross-brick couplet method typically yields low values for mortars whose tensile bond strengths are high.

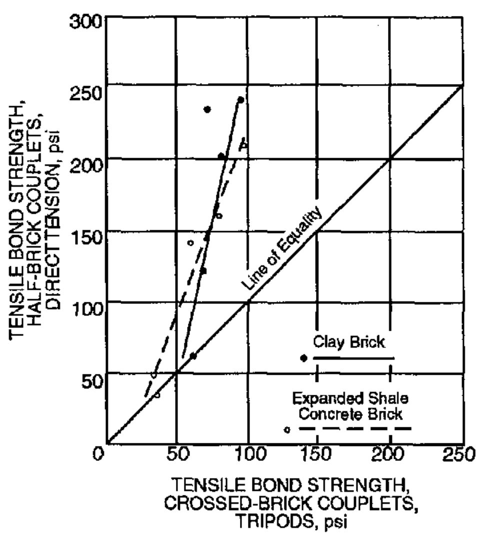


Figure 7—"Cross-Brick Couplet" method gives unusually low values for mortars whose tensile bond strengths are high.

Comparison of single beam flexural test results (similar to ASTM E 518) and bond wrench test results (similar to ASTM C 1072) reported at the Second Canadian Masonry Symposium [Ref. 6] indicates that average values obtained by these two methods are comparable.

A cooperative study [Ref. 7] designed to establish the bonding characteristics of mortars with simulated and closely controlled concrete masonry units indicates that present mortar materials have the potential for developing high bond strengths. The ASTM C 1072 Test Method was used to measure bond strengths of specimens. These laboratory tests – involving an array of mortar materials – showed within-laboratory coefficients of variation ranging from 10% to 25%. Specimens tested in this study were fabricated and cured using procedures intended to minimize testing variability. Therefore, this range of variability can be taken as an indication of the precision of the method under optimum conditions.

McGinley [Ref. 8 & 9] developed a calibration device to investigate the performance of the ASTM C1072 apparatus in producing assumed linear stress distributions on test specimens during loading. This work has identified several critical details that need to be considered when performing testing using the bond wrench. He has proposed modifications that would reduce stress concentration effects and the rotation of the upper clamp, increase the stiffness of the apparatus, and ensure that the lower section of the prism is not loaded during testing. His work indicates that a low and uniform loading rate tends to improve consistency. It also indicated that reducing the axial stress component of the load (by increasing the lever arm length) may reduce variability and improve comparability to results obtained using the ASTM E 518 test.

A more recent and comprehensive study conducted at the National Concrete Masonry Association included wall testing and assembly testing of concrete masonry specimens fabricated and cured under the same controlled conditions. Prism specimens were tested using a bond wrench that had been modified to permit testing standard-sized concrete masonry units. Individual correlation between results of wall and prism tests varied, but average results indicate that average bond test results from E 72 wall tests are essentially equivalent to results obtained from testing prism samples using a bond wrench apparatus. The wall test results generally exhibited less variability than results from the prism tests.

INTERPRETATION OF RESULTS

An idealized experimental design involves comparison between a test combination and a control combination. During research testing, every effort is or should be made to identify significant variables and to control these variables. During quality control testing, past results are compared with newly obtained results using identical testing procedures to ascertain the degree of quality control being exercised.

All experimentation and testing involves isolating, controlling, and measuring variables. The person documenting the testing program should identify the test methods and procedures used during the experimentation and record exceptions. Strict compliance to a standard test method is implied without reported exceptions. Test results must be interpreted based on knowledge and understanding of the boundary conditions that prevailed during experimentation.

Correlations between physical properties of materials and performance characteristics of assemblies involve testing of both individual materials and assemblies. However, properties measured on component materials often do not represent the performance of that material in an assembly. For example, ASTM C 270, the *Standard Specification for Mortar*, provides procedures for sampling, testing and reporting physical tests of mortars. The laboratory tests prescribed by ASTM C 270 bring cementitious materials together with aggregate and water to ascertain if the resulting test mortar yields the desired characteristics and functions normally. Controls established by the procedure for preparing the ASTM C 270 test mortar are much different than would be utilized in mixing mortar used to construct a masonry test assembly or a masonry wall. In particular, the water content of the laboratory mortar mix is much lower than would be used to fabricate a masonry assembly. Mortar test specimens are placed in non-absorptive cube molds rather than between absorptive masonry units. As a result of these differences, correlations between mortar properties determined in accordance with ASTM C 270 to the actual performance of mortar in masonry assemblies are difficult or impossible to establish. Bond strength of masonry remains an elusive characteristic of the combined materials which can only be effectively evaluated by bond strength testing of assemblies.

REFERENCES

1. Anderegg, F. O., "Practical Methods for Testing Masonry Mortar Cements," *Rock Products*, June, 1932, Chicago.

2. Anderegg, F. O., "Some Properties of Mortars in Masonry," *Proceedings of the American Society for Testing Materials*, Vol. 40, 1940, ASTM, Philadelphia, pp. 1130-1142.

3. Anderegg, F. O., "The Effect of Brick Absorption Characteristics Upon Mortar Properties," *Proceedings of the American Society for Testing Materials*, Vol. 42, 1942, ASTM, Philadelphia, pp. 821-836.

4. Fishburn, C. C., "Effect of Mortar Properties On Strength of Masonry," National Bureau of Standards Monograph 36, United States Department of Commerce, 1961, Washington.

5. Kuenning, W. H., "Improved Method of Testing Tensile Bond Strength of Masonry Mortars," *Journal of Materials*, Vol. 1, No. 1, 1966, ASTM, Philadelphia, pp. 180-202.

6. Hughes, D. M., Zsembery, S., "A Method of Determining the Flexural Bond Strength of Brickwork at Right Angles to the Bed Joint," Proceedings of the Second Canadian Masonry Symposium, Ottawa, 1980, pp 73-86.

7. Hedstrom, E. G., Tarhini, K. M., Thomas, R. D., Dubovoy, V. S., Klingner, R. E., Cook, R. A., "Flexural Bond Strength of Concrete Masonry Prisms Using Portland Cement and Hydrated Lime Mortars," *The Masonry Society Journal*, Vol. 9, No. 2, February 1991, The Masonry Society, Boulder, CO, pp. 8-23.

8. McGinley, W. M., "Flexural Bond Strength Testing – An Evaluation of the Bond Wrench Testing Procedures," *Masonry: Design and Construction, Problems and Repair, ASTM STP 1180*, ASTM, Philadelphia, 1993, pp. 213-227.

9. McGinley, W. M., "Bond Wrench Testing – Calibration Procedures and Proposed Apparatus and Testing Procedure Modifications," *Proceedings of the Sixth North American Masonry Conference*, The Masonry Society, Boulder, CO, 1993, pp. 159-172.

Portland Cement Association *5420 Old Orchard Road, Skokie, Illinois 60077-1083*

An organization of cement manufacturers to improve and extend the uses of portland cement and concrete through market development, engineering, research, education, and public affairs work.

Printed in U.S.A.

IS277.01M