MASONRY INFORMATION

Factors Affecting Bond Strength of Masonry

INTRODUCTION

The development of bond between masonry mortar and masonry units is significant to the performance of the masonry in service. Intimate contact between mortar and unit aids in resistance of water penetration. In unreinforced masonry designed by working stress analysis, the adhesion of mortar to units is relied upon to resist flexural tension stresses resulting from eccentric axial loads, or out-of plane loads, or both. These are two distinctly separate aspects of bond. The first relates to the extent of bond or degree of contact between mortar and unit. The second is the bond strength of masonry. Both are functions of several variables associated with the specific mortar and units considered, as well as the conditions under which they were assembled and cured.

Research has shown that the extent of bond and bond strength do not necessarily relate to one another. It is quite possible to develop excellent and intimate contact between mortar and unit using combinations of materials that yield relatively low bond strengths. Conversely, a high bond strength does not necessarily mean that complete and intimate contact between mortar and unit has been achieved.

Several standard test procedures have been established to measure the bond strength between mortar and unit (see PCA publication IS277, *Bond Strength Testing of Masonry*). Although the precision of these methods has not been determined and relationships between test results and in-place performance are still being investigated, there is a fairly large body of published research available from which to evaluate the test procedures and gather information on factors affecting bond strength. This document summarizes findings of research investigating the relationship of bond strength to material properties, fabrication procedures, and curing conditions.

EFFECT OF SPECIFIC VARIABLES

Variables affecting the bond strength include:

- Mortar properties
- Type of masonry unit
- Techniques used to fabricate masonry assemblies
- Specimen conditioning between fabrication and testing
- Testing procedures

Mortar Properties

ASTM C270, the Standard Specification for Mortar for Unit Masonry, classifies mortars as Types M, S, N, or O. These mortars may be specified either under the property specifications or the proportion specifications of that standard. Under the property specifications, laboratory prepared and tested mortars of each designation by type must meet specific requirements for compressive strength, water retention, and air content. The proportion specifications define a range of acceptable proportions for mortar ingredients for each mortar type. Requirements are given for both cement-lime mortars and masonry cement mortars under each set of specifications as indicated in Tables 1 and 2. Mortar properties which influence bond strength development include cement content, water retentivity, air content, and flowability as related to water content.

Cement content. Increased portland cement content of mortar generally provides increased bond strengths. Melander and Conway [Ref. 1] documented this relationship for tests conducted on concrete masonry brick and portland cement-lime mortar assemblies. They developed a mathematical model for the relationship under laboratory test conditions. Wright [Ref. 2] also observed a correlation between increased cement content of mortar and higher bond strengths

Table 1. Proportion Sprcification Requirements*

Mortar	Type	Proportions by Volume: Portland Cement or Blended Cement	Masonry Cement M	Masonry Cement S	Masonry Cement N	Hydrated Lime	Aggregate Ratio
Cement-lime	M	1	–	–	–	1/4	Not less than 2 1/4 and not more than 3 times the sum of the volumes of cement and lime used.
	S	1	–	–	–	over 1/4 to 1/2	
	N	1	–	–	–	over 1/2 to 1 1/4	
	O	1	–	–	–	over 1 1/4 to 2 1/2	
Masonry cement	M	1	–	–	1	–	
	M	–	1	–	–	–	
	S	1/2	–	–	1	–	
	S	–	–	1	–	–	
	N	–	–	–	1	–	
	O	–	–	–	1	–	

* Adapted from ASTM C270.

Table 2. Property Specification Requirements*

Mortar	Type	Minimum 28-Day Compressive Strength, psi (MPa)	Minimum Water Retention, %	Maximum Air Content, %	Aggregate Ratio
Cement-lime	M	2500 (17.2)	75	12	Not less than 2 1/4 and not more than 3 times the sum of the volumes of cement and lime used.
	S	1800 (12.4)	75	12	
	N	750 (5.2)	75	14**	
	O	350 (2.4)	75	14**	
Masonry cement	M	2500 (17.2)	75	–**	
	S	1800 (12.4)	75	–**	
	N	750 (5.2)	75	–**	
	O	350 (2.4)	75	–**	

* Adapted from ASTM C270.

** When structural reinforcement is incorporated in the cement-lime or masonry cement mortar, the maximum air content shall be 12% or 18% respectively.

for masonry specimens constructed using concrete masonry brick. Their study included laboratory formulated masonry cement mortars and portland cement-lime mortars.

Some studies [Ref. 3] involving masonry assemblies constructed of cement-lime mortars and clay masonry unis have reported optimum bond strengths using cement contents in the range of Type S proportions with little or no increase when Type M proportions were used. That fact is probably related to the relative workability and water retentivity of the two types of mortars, coupled with the testing and curing conditions under which the experimental programs were conducted. Current design criteria adopted by model codes and design standards in the United States are consistent with the finding that little or no increase in bond strength is achieved by the use of Type M mortars as compared to Type S mortars. These documents (Uniform Building Code and ACI 530/ASCE 5/ TMS 402, which is adopted by reference in the BOCA Code and Standard Building Code) assign the same allowable flexural tensile stress values for masonry constructed using Type M mortar as for Type S mortar. (Allowable flexural tensile stress values listed in the codes and standards are used in the design of unreinforced masonry in which the flexural tensile resistance of the masonry is taken into consideration.) Reduced allowable stress values are listed for Type N mortars since lower bond strengths are typically obtained with Type N mortar than with Type S mortar due to the reduction in portland cement content.

Some tendency for bond strengths to increase as compressive strengths of mortars increase was observed by Fishburn [Ref. 4]. However, subsequent studies have reported little or no correlation between the compressive strength of mortar and bond strength [Ref. 5 & 6]. Since compressive strengths are influenced by cement content, one would expect bond strengths to increase with increasing cement content. However, other factors that increase bond strength, such as increased water content, tend to reduce the compressive strength of mortar. That fact may explain the lack of correlation between bond strength and compressive strength in many studies.

Water retentivity. Conflicting findings on the relationship of water retentivity to bond strength have been reported. Ritchie and Davison [Ref. 7] indicated that improved bond strengths were achieved with mortars having higher water retentivity – particularly when used with high-absorption units. However, other studies have reported either no significant improvement in bond strength with increased water retentivity [Ref. 5] or even a reduction in bond strength for mortars having higher water retention values [Ref. 8]. Apparently, specific study conditions greatly influence test results. In particular, limitations of the water retention test, procedures used to control water retention values for test mortars, and different curing and fabrication procedures have probably contributed to divergent observations. *The most convincing statement with respect to water retention of mortar is that a compatible balance with unit properties is needed. That is, fluid paste from the mortar needs to readily flow into the surface irregularities of the masonry unit, while sufficient water for cement hydration must be retained in the mortar system.* It should also be noted that the standard ASTM test used to measure water retention actually measures the ability of a mortar to retain its flow under suction rather than the ability of mortar to retain its mixing water.

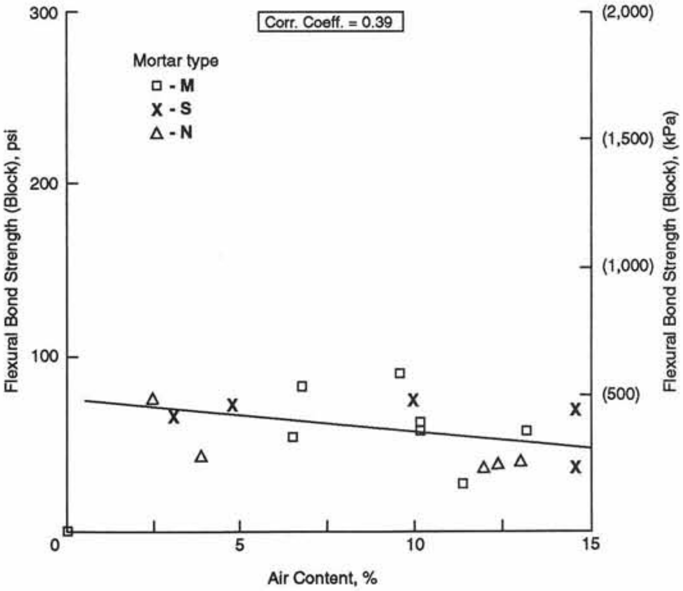

Fig. 1 — Ribar reported a linear relationship between mortar air content and bond strength. The low correlation coefficient indicates that other variables also significantly affect bond strength [Ref. 9].

Air Content. Air content of masonry mortars generated during mixing is influenced by the cementitious materials, sand, mixing procedures, water content, ambient temperature, and air-entraining admixtures. As measured by ASTM test methods on the fresh mortar, air content includes entrained air and entrapped air. Petrographic examination of the hardened mortar can be used to distinguish entrained air from entrapped air based on the air void size, shape, and spacing. Entrained air within the masonry mortar improves workability and durability of the mortar, while serving as a water reducing agent.

As air content of mortar is increased, bond strength tends to decrease provided other factors are held constant. The relationship is generally linear, as indicated in Fig. 1. The data does not support the frequently stated contention that air content levels below 10 or 12 percent do not affect bond strength; nor is placing a limit on air content of mortar an effective means of predicting or controlling the bond strength of masonry. Excellent bond strengths can be achieved using air-entrained mortars. Air content is simply one of several variables that affect bond strength. Its relative significance depends on the degree of control exercised on other variables.

Illustrating that principle, experimental work by Wright [Ref. 2] indicated that under controlled laboratory conditions of mortar mixing, specimen fabrication, and curing, the percentage of portland cement contained in the mortar had four times as much impact as the percentage of air on bond strength. Robinson and Brown [Ref. 5] reported bond strengths ranging from 30 to 179 psi [200 to 1230 kPa] for masonry assemblies fabricated with mortars having essentially equivalent air contents (18 to 19 percent). These air contents were obtained using different air-entraining agents or different procedures. They postulate from this data that, in addition to air content level, the type of air-entraining agent and bubble structure influence bond strength. Interestingly, Kampf [Ref. 10] observed improved bond strengths with increasing air contents of mortars when used with a high suction (IRA) brick, but noted a reduction in bond strengths with increasing air content of mortars when used with low suction brick. He concluded that with high suction units, mortar characteristics of workability and water retention are more significant to bond strength development, while the cohesive or tensile strength of the mortar tends to dominate bond strength development with low suction units.

Water Content. Past research [Ref. 5, 6, & 7] indicates that bond strength is significantly influenced by the water content of the masonry mortar at the time of specimen fabrication. Mortars with increased water contents produced higher bond strengths. This finding indicates that a more fluid mortar "wets out" the interface between mortar and unit better. Specification ASTM C 270 is consistent with this finding since C 270 stipulates mixing mortar "...with the maximum amount of water to produce a workable consistency." Assuming that evaluation of workable consistency includes consideration of unit characteristics, water additions to masonry mortar are self regulating. That is, too low water contents affect workability and too high water contents affect joint thickness as well as workability. Although laboratory compressive strength of mortar decreases with increased water content, bond strength increases, as shown in Fig. 2.

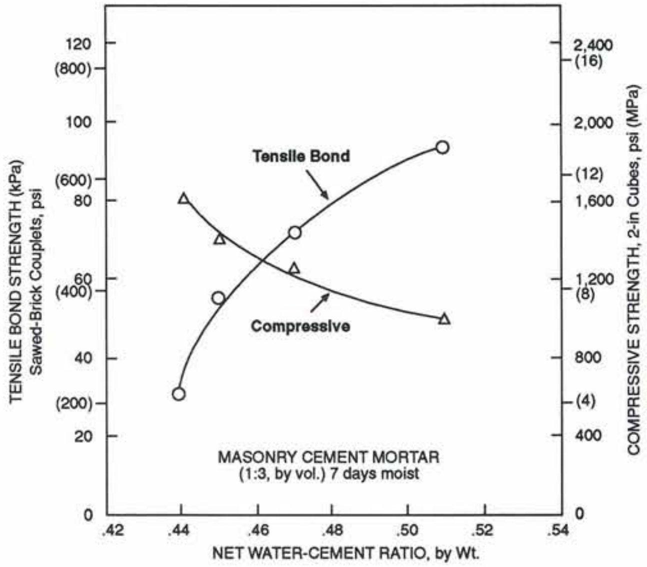

Fig. 2 — Increased mortar water content reduces compressive strength but increases bond strength [Ref. 11].

This finding also supports the practice of retempering mortars as frequently as necessary provided the mortar has not stiffened due to cement hydration. Specification ASTM C270 stipulates that mortar be used within 2 1/2 hours from the time of initial mixing to preclude the use of mortar that has hardened from hydration of the cement.

Masonry Units

Bond strength is significantly influenced by the composition and physical characteristics of the masonry units – particularly surface characteristics. Clearly, loose sand particles, dirt, or other contaminants on the surface of units will reduce the ability of the mortar to adhere to the unit. Surface texture of units also affects bond strength. A smooth, even surface limits mechanical keying with mortar, resulting in lower bond strengths than would be achieved with a unit having a rough textured surface.

For clay masonry, initial rate of absorption, later age absorption characteristics, and bedded surface texture of the unit are important. The initial rate of absorption (IRA) of the unit attracts the mortar to its surface. Once bedded and during mortar setting and hardening, mortar must retain sufficient water to promote cement hydration and crystal growth at the brick-to-unit-interface. Both surface texture and mortar composition influence this occurrence. Additionally, water absorbed by the unit is available later for continued hydration of the cement in the masonry mortar.

Several studies have documented a relationship between IRA and bond strength. Palmer [Ref. 12] observed that optimum bond strengths were obtained using units having moderate suction, (IRA in the range of about 20 g per 30 sq in. (194 sq cm) per minute), as shown in Fig. 3. Subsequent data reported by Ritchie [Ref. 7], Dubovoy [Ref. 6], and McGinley [Ref. 13] support the theory that optimum bond strengths are obtained using units having moderate suction. Kampf's work included wire cut and molded brick having IRAs ranging from approximately 6 to 75 g per 30 sq in. (194 sq cm) per minute. He reported that bond strengths tended to be lower as IRAs increased, as shown in Fig. 4. Bond strengths developed using units having similar IRAs were lower for molded brick than for wire cut brick, reflecting the influence of surface texture.

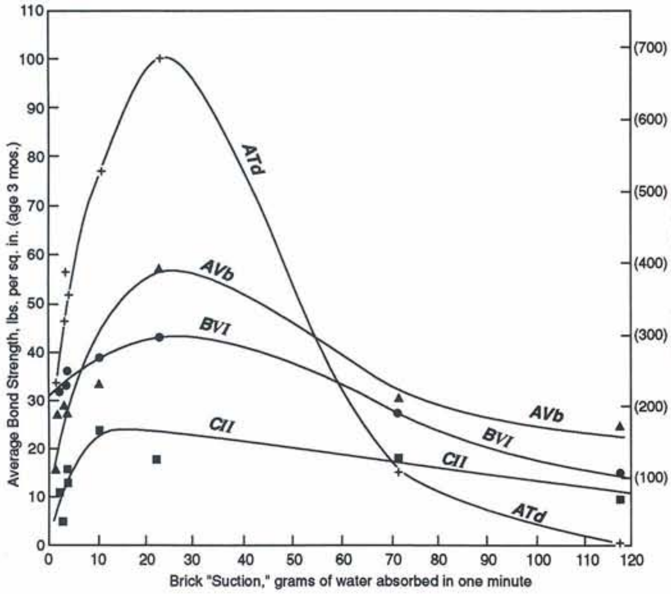

Fig. 3 — Palmer observed optimum bond strengths for brick having moderate initial rates of absorption (IRA) [Ref. 12].

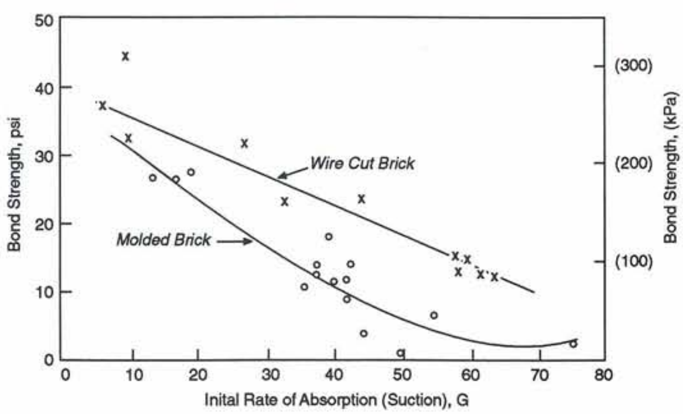

Fig. 4 — Kampf observed a trend of lower bond strengths with high IRA units and noted a difference between bond strengths achieved using wire-cut brick as compared to molded brick [Ref. 10].

Other research reports have questioned the significance of IRA with respect to bond strength development [Ref. 5 & 14], and it should be noted that IRA is a single variable associated with a component material of the masonry assembly. Unit characteristics such as surface texture and pore structure also affect bond strength and can be more significant than IRA. Dubovoy and Ribar [Ref. 6] developed a procedure for quantifying the surface texture of units in a single parameter called the contour ratio. They developed a model equation for the bond strength of masonry that included the contour ratio and the square of the IRA, as shown in Fig. 5. Predicted bond strength values show fairly good agreement with actual measured values and demonstrate that properties of clay masonry units affect bond strength at least as much as properties of masonry mortars.

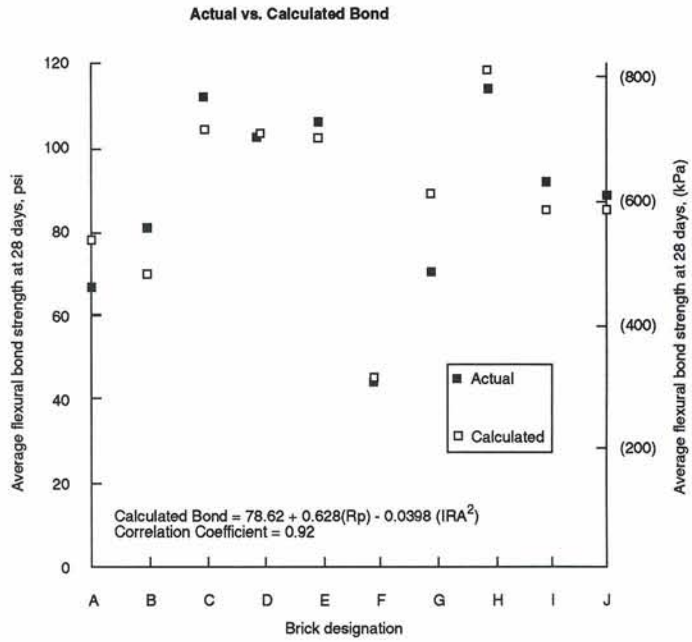

Fig. 5 — Dubovoy and Ribar developed a model equation for bond strength using brick texture (Rp) and the square of the initial rate of absorption (IRA^2) as independent variables [Ref. 6].

Research by Ritchie and Davison [Ref. 7] indicated that improved bond strengths are achieved by wetting high IRA brick. This finding is consistent with the advisory note contained in ASTM C216 which recommends that clay masonry units having an IRA over 30 g/ 30 sq in. per minute be dampened to reduce the effective IRA to a value below 30 g/ 30 sq in. per minute.

Some studies [Ref. 15] have indicated that higher bond strengths are achieved with clay masonry units than with concrete masonry units. However, published data involving bond tests of these two materials under comparable conditions of testing are very limited. Recent research conducted by the National Concrete Masonry Association indicates that very high bond strengths may be achieved in concrete masonry assemblies when Type M or S mortars are used and when the assemblies are adequately cured. Bond strengths between high strength mortars and concrete masonry units can in fact exceed the tensile strength of the concrete masonry units themselves under optimum curing conditions.

Specimen Fabrication

The preparation of test specimens for measuring bond strength varies. This preparation may involve detailed laboratory procedures or simply "qualified masons" using their own procedures on the project. Laboratory procedures concentrate on alignment, mortar bed thickness, pressure applied during setting of upper units, and tooling of joints. Specimens fabricated at the jobsite involve different craftsmen performing the above mentioned tasks without benefit of frames and guides and under varied climatic conditions.

Bond strength is highly dependent on the techniques used to bring mortar and unit together to form a masonry assembly. Important variables are: the elapsed time between applying bedding mortar on a unit and placement of the unit covering that mortar joint, the compaction of the mortar during placement of the unit, and subsequent disturbance of a unit after initial placement.

Elapsed time. Bond strength decreases as elapsed time between the application of bedding mortar to a unit and placement of the next unit increases [Ref. 7, 10]. The explanation for this is related to the previously noted relationship between bond strength and mortar water content. Mortar that is placed in contact with an absorptive masonry unit mortar immediately begins to lose moisture to that unit. Thus, the mortar will have a lower water content and a stiffer consistency when the upper unit is placed, reducing the bond between mortar and unit. Absorption characteristics of the unit, water retentive properties of the mortar, and ambient conditions also influence the significance of elapsed time on bond strength.

Compaction of mortar. As a unit is placed, it is pushed into the existing mortar bed, extruding excess mortar from the joints. This physical action forces mortar into surface irregularities of the unit. Richie and Davison [Ref. 7] compared fabrication procedures which included use of a "2-pound drop-hammer," a "4-pound drop-hammer," and a "bricklayer." They observed that bond strengths were greater for specimens fabricated using the heavier drop-hammer. The best results were achieved by the mason using normal bricklaying techniques. Some laboratory test procedures incorporate the use of drop-hammers in the fabrication of specimens to control the variable of workmanship and eliminate the need to employ a trained mason to fabricate specimens. It should be recognized that these procedures are primarily for comparative evaluation of materials. Bond values obtained in the laboratory are likely to differ from those achieved under field fabrication conditions.

Realigning units. Retaining undisturbed contact between mortar and unit immediately after placement is required to maintain optimum development of bond strength. If mortar has stiffened prior to final alignment, complete loss of bond is likely. Kampf [Ref. 10] studied the effect of disturbing the top unit of crossed-brick couplet specimens at various time intervals after placement. He observed that the elapsed time during which brick could be realigned without destroying the bond is greatest for low-suction brick and high water-retentive mortars. For one specimen, bond was destroyed by movement 15 seconds after placement. This reinforces the recommendation that once a unit is placed, alignment should be immediate. Also, any forces exerted to achieve alignment should be toward the existing mortar bed.

Effect of Curing Conditions

Conditioning of the test specimen during the period from fabrication until testing significantly influences the measured bond strength. Because portland cement paste requires a moist environment to maintain its relative humidity (above about 80%) for continued cement hydration, any condition promoting drying of the masonry mortar affects bond strength. Additionally, any drying of a masonry assembly produces restrained and differential shrinkage of the masonry mortar within the assembly. These shrinkage stresses, unless equilibrated, affect the measured bond strength. The most significant portion of the mortar prone to this effect is the mortar at the joint surface, the same mortar surface that receives the greatest tensile stress during flexural testing.

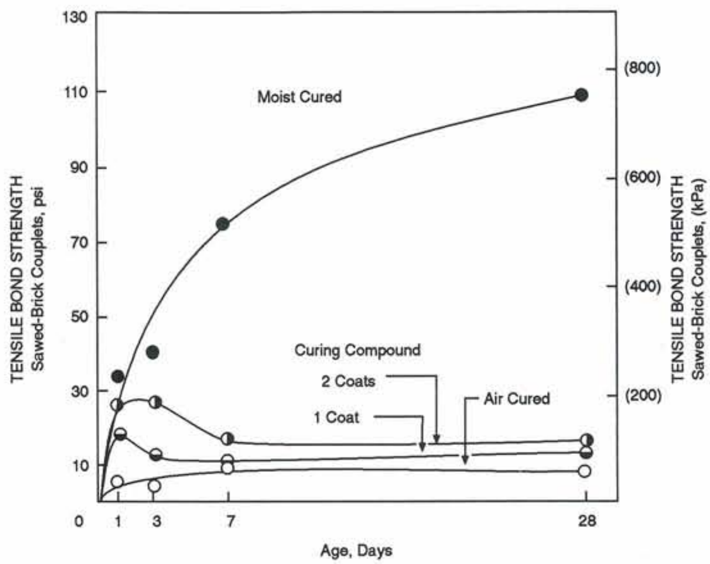

Fig. 6 — Curing conditions affect bond strength results [Ref. 11].

Ideally, with the objective of establishing the bond strength of in-place masonry, all masonry test assemblages should be subject to the same curing conditions as the actual walls they represent. However, to remove climatic conditions as an uncontrolled variable, laboratory fabrication of specimens is completed in a controlled environment. ASTM C1072, the Standard Method for Measurement of Masonry Flexural Bond Strength, recommends that "... laboratory air be maintained at a temperature of 75 ± 15°F (24 ± 8°C), with a relative humidity between 30 and 70 percent." These conditions do not constitute an effective curing environment, so some test methods require "self curing," obtained by enveloping test specimens within plastic bags. Recent comparisons of bond strengths of damp cured concrete masonry specimens as compared to specimens cured in laboratory air indicate that over a 300% increase in bond strength is achieved by damp curing.

As noted in Fig. 6, bond strength is affected by the period of moist curing and storage in air. To establish the bond strength potential of a combination of mortar and masonry units, the test specimens should be cured in a moist environment until tested.

Effect of Test Method on Bond Strength

Different test procedures produce different measured bond strength results. For a more detailed discussion of the variables involved in testing and the effect of various standard test methods, see PCA Publication *IS 277, Bond Strength Testing of Masonry*.

SUMMARY

Development of bond strength in masonry is a complex process dependent on many variables related to materials, fabrication, curing, and testing. Several of these parameters are interdependent. Certain general relationships have been established by isolating and measuring the effect of specific variables. However, it is important to note that relationships exhibited under controlled experimental conditions may be obscured in actual application by the effect of changes in other parameters. Perhaps the most significant finding that can be gleaned from a review of the numerous investigations with respect to bond strength is the observation that it is a combined property of the mortar and the unit together. It cannot be accurately predicted from individual characteristics of the component materials.

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