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BOND
OF
MORTAR TO MASONRY UNITS

Factors Influencing Strength, Extent, and Durability of Bond

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Preface

Over the years considerable research has been conducted on masonry mortar, some of which has been obscure or forgotten . . . and much of it contradictory in its conclusions and/or interpretation of the findings . . . and there is often disagreement among the researchers on the significance of tests, etc. Yet, preponderant or majority opinions on this collective research is often possible to glean. To this end the National Lime Association's staff has made a study of what appears to be the most significant research in the mortar field.

The results of this study are being summarized in a series of articles categorized into the principal properties and considerations of mortar, such as durability, efflorescence, bond, volume change, strength, and workability, along with selected bibliographies. The third article of this series deals with bond, covering such aspects as bond strength, bond extent, and durability of bond. The earlier articles dealt with mortar durability and strength, respectively.

One inescapable general conclusion from this study is that an overwhelming majority opinion among the independent authorities consistently substantiated the need for *both* lime and portland cement in a well balanced, all-purpose mortar. The lime referred to is either hydrated lime or lime putty made from quicklime and may be either dolomitic or high-calcium types. This should never be confused with pulverized limestone (calcium carbonate) that is sometimes erroneously called "lime", and which is inert in mortar and has none of the properties inherent with burned lime products. So, whether a conventional lime-cement mortar or a prepared one-bag mortar is used, be sure the mortar contains a bonafide lime that meets ASTM Specification C 207 or C 5—and enough of it.

Bond of Mortar to Masonry Units

Factors Influencing Strength, Extent, and Durability of Bond

Of the numerous factors contributing to sound masonry, bond between the units and the mortar is generally recognized as a very important factor, perhaps *the* most important. Obviously, with strong, durable bond, walls remain both watertight and strong enough to withstand stresses from high winds, vibrations, etc.

It is important at the outset to recognize three salient points:

1. Bond, as related to masonry construction, actually has two counterparts—*bond strength* and *extent of bond.* With most mortar-masonry unit combinations, the two paradoxically are incompatible, e.g., high bond strength generally does not guarantee full extent of bond.

2. Bond strength (generally referred to as tensile bond strength) is determined principally by the A.S.T.M. crossed-brick couplet test, in which the force needed to pull the units from the mortar is measured. Modifications of this test have been made, and other small scale bond tests have been developed; but none of the current tests are completely satisfactory, mainly because they lack reproducibility and are unrealistic to field conditions.

On the other hand, the various bond strength tests can be used to determine visually the extent of bond. The extent of bond can also be ascertained indirectly by various laboratory wall permeability or leakage tests.

3. For sound masonry it is essential not only to have adequate bond strength and complete extent of bond but also to have *durable bond,* starting with initial hardening and continuing throughout the life of the structure. Separation cracks should not develop at the mortar-unit interface, thereby impairing the bond.

This report will show how high lime mortars (like the 1:2:9 cement, lime, and sand mix) contribute to producing tight, durable bond, hence watertight walls, even though their tensile bond strength, as determined in the laboratory, may only be moderate in value. In contrast, high cement mortars (like the 1:¼:3) generally exhibit high laboratory bond strengths, but have poor extent of bond and also lack durable bond due to a tendency to develop separation cracking. Principal reasons for lime's superiority over portland cement in producing intimate and durable bond are its higher degree of plasticity and water retention, and its greater fineness and inherent stickiness, which permit joints to be filled more readily and completely. Its ability to heal minute cracks and fill minute voids (autogeneous healing) also contributes to better bond.

This report will also show that high air content mortars, as produced through the use of most limestone-based masonry cements, are lacking in both extent of bond and tensile bond strength. Their poorer bond is explained by the myriad of microscopic air bubbles existing at the mortar-unit interface which prevent intimate contact between the mortar and units.

Factors Affecting Bond—The subject of bond of mortar to masonry is complex, judging from the large number of factors which exert an influence. Included are such variables as *type of mortar* (its workability, water retention, initial flow, setting characteristic, air content, strength, volume change, resilience, etc.); *type of masonry unit* (its absorption, permeability, surface characteristics, etc.); and *workmanship* (filling of joints, degree of pressure applied to masonry unit, type of tooling, etc.). These various factors will be considered individually and collectively, with appropriate references made to important research work of the past. First, factors affecting bond strength will be covered, then extent of bond, and lastly, bond durability.

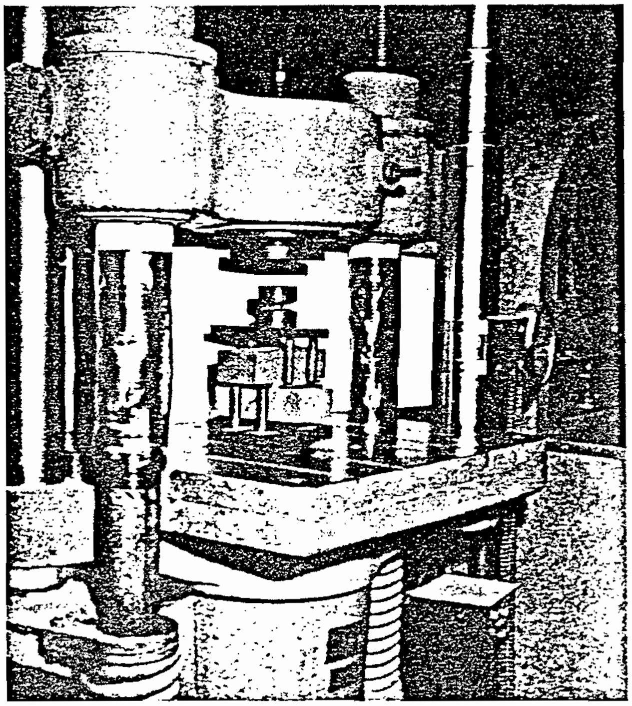


FIG. 1. Crossed-brick couplet in position for tensile bond strength determination.

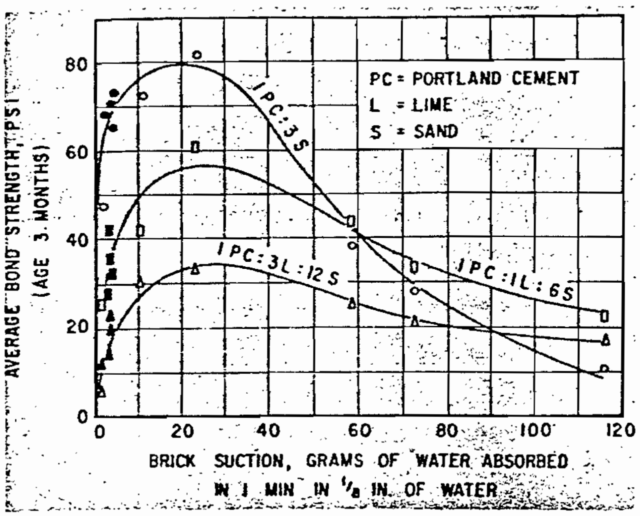


Fig. 2. Relation of tensile bond strength to brick suction and mortar composition. (Palmer and Parsons)[1]

Bond Strength Test—As stated earlier, the crossed-brick couplet test, "Tentative Method of Test for Bond Strength of Mortar to Masonry Units" (ASTM E-149), is the most widely used small scale bond test, although it is far from being completely satisfactory. The test is fairly simple to perform, and is used chiefly for making relative evaluations of mortars and of masonry units. In this test a mold is used for forming the mortar joint between the crossed bricks, and the couplet is assembled and cured with meticulous care. In the testing apparatus, two three-pronged jigs are used to force the bricks apart, with the load being applied gradually to the upper jig, as shown in Figure 1. Generally, tensile bond failure occurs within two minutes. In nearly all cases failures occur at the plane between the top of the mortar and the top brick.

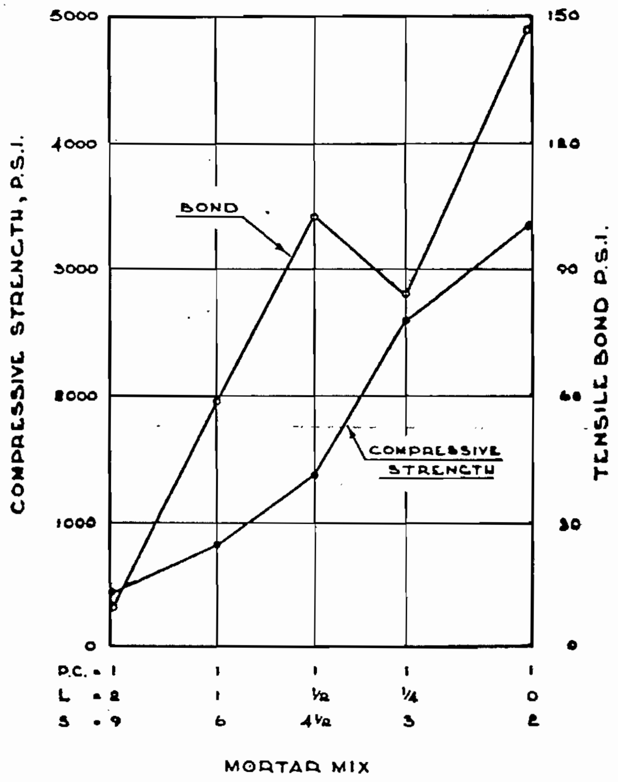
BOND STRENGTH FACTORS

The two most important factors affecting tensile bond strength are the type of mortar (particularly its water retention, initial flow, air content and strength) and the type of brick (particularly its suction). Generally, high bond strength is attained through use of mortars having high water retention, high initial flow, high strength and low air content, and masonry units having moderate suction and roughened surfaces. Applying pressure during bricklaying is also conducive to high bond strength, although it is detrimental to tap or move the units once the mortar has begun to harden.

Brick Suction—The classic 1934 National Bureau of Standards study by Palmer and Parsons,[1] which involved 50 mortar types and six makes of brick, proved the important relation of brick suction, mortar strength, and water retention to bond strength. In Figure 2, the authors demonstrate that for each mortar type, the bond strength reached a maximum with 20 gm. suction brick, then fell off considerably as suction increased to high values.

The Structural Clay Products Institute subscribes closely to the Palmer-Parsons research, stating in its Technical Notes on Mortar[2] that mortar bonds best to brick whose suctions are 5-20 gm. *at the time of laying*. If the suction exceeds 60 gm., the bond may be extremely poor, and soaking the brick prior to laying is imperative; however, the wetted brick should be surface dry. For low suction brick (less than 5 gm.), the mortar should have a low water content and moderate water retention.

Mortar Strength—Figure 2 also shows that for low to moderate suction brick the bond strength increases with the portland cement content and decreases with the lime content; however, for high suction brick (generally over 60 gm.), the bond strength of the straight cement mortar is lower than that of the medium to high lime mortar.



NOTE: INITIAL FLOW of MORTAR = 140 PERCENT SPECIMENS FOR BOND TESTS WERE BUILT of SAND and GRAVEL BLOCK and CURED in AIR at 73°F and 75% R.H.

Fig. 3. Relation of tensile bond strength of heavyweight concrete block couplets to compressive strength of mortar (Redmond).[3]

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[1] Number refers to list of references appended to this report.

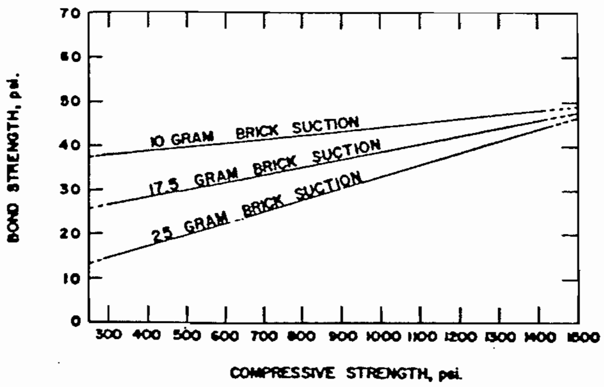


FIG. 4. Relation of tensile bond strength to compressive strength of masonry cement mortar and brick suction. (Fishburn) [5]

Using the A.S.T.M. crossed-brick couplet test as a basis, S.C.P.I.[2] suggests that for *maximum bond strength,* the optimum lime to cement ratio lies between the values of 1 and ¼. Accordingly, the Institute recommends the use of an A.S.T.M. Type S mortar (1:½:4½) for maximum bond strength although they also state that the available data is inconclusive.

The National Concrete Masonry Association carried out a mortar bond study from 1956 to 1962 at the University of Toledo under the direction of E. L. Saxer, which was discussed by T. B. Redmond.[3] A total of 592 concrete block piers, 16 masonry beams, and nine block wallettes were tested at Toledo. Figure 3, based on tests of block couplets, shows that tensile bond strength is closely related to compressive strength of the mortar, with the bond strength increasing with the cement content and decreasing with the lime content. From this study, it is suggested that for minimum tensile bond strength of 75 p.s.i., the proportion of portland cement to lime should not be less than 3 to 1, and the mortar compressive strength should exceed 2500 p.s.i.

C. C. Fishburn,[4,5] in his extensive study of masonry cements at the National Bureau of Standards during the 1950's, also reported an increase in tensile bond strength with an increase in mortar compressive strength. This is shown in Figure 4, taken from his 1963 Building Research Institute paper. Note that the graph also verifies the earlier discussion relating brick suction to tensile bond strength.

Water Retention—High water retention in mortar is conducive to good bond strength, particularly with high suction brick. This was emphasized by Palmer and Parsons, in Figure 2, when they stated that the sharp descent in bond strength of the straight cement mortar with brick having more than 30 gm. suction was due to the low water retention of the mortar. In contrast, both the 1:1:6 and 1:3:12 mortars exhibited a gentler decline in bond strength with higher suction brick, due primarily to the higher water retention imparted to the mortar by the use of lime.

The importance of water retention was also brought out by Ritchie and Davison[6] of the Canadian National Research Council in a study involving five brick stack-bond panels. As water retention increased, tensile bond strength also increased, as did resistance to moisture penetration.

J. F. Ryder,[7] British Building Research Station, subjected small brick panels to a centrally applied transverse load, and noted that breakage in panels made with high suction brick and high water retention mortar occurred through the brick, indicating excellent bond. In contrast, where the mortar had low water retention and poor bond, the breakage occurred at the mortar interface and not through the brick.

Initial Flow—It is generally accepted that bond strength increases as initial mortar flow increases. This was borne out in research by Saxer,[3] Fishburn,[5] Ritchie and Davison,[6] Whittemore and Dear,[8] and others. This being the case, it is advisable to use maximum mixing water compatible with good workmanship; it also is important to reduce the time lapse between mortar spreading and brick placing, particularly when high suction brick and/or low water retention mortar are used. Because high lime mortars have high water retention, the time interval is not as critical as with high cement mortars.

Air Content—Considerable data exists proving that tensile bond strength decreases as air content

TABLE I. *Tensile Bond Strength Using Conventional Mortar and Air-Entrained Mortar**

Mortar	Wire Cut Brick		Smooth Common Brick	
	Range	Average	Range	Average
1:1:6 without a-e agent (3% air)	92-149 p.s.i.	117 p.s.i.	47-105 p.s.i.	75 p.s.i.
1:1:6 with a-e agent (18.5% air)	4-36 p.s.i.	16 p.s.i.	7-39 p.s.i.	22 p.s.i.

* Couplets cured for 7 days in fog room at 70° F., followed by 21 days in laboratory air.

TABLE II. *Tensile Bond Strength Using Common Brick**

Mortar	Range	Average
1:1:6 (4.4% air)	68-140 p.s.i.	90.9 p.s.i.
1:1:6 (23.6% air)	15- 53 p.s.i.	29.0 p.s.i.
1:2:9 (3.1% air)	64-102 p.s.i.	81.1 p.s.i.
1:2:9 (24.0% air)	0- 38 p.s.i.	21.2 p.s.i.

* Cured for 28 days in laboratory (as in Table I), followed by 3 months of field curing.

increases, with strengths being extremely low when air content exceeds 16%. Results of one National Lime Association member company testing program are presented in Tables I and II. In this study the A.S.T.M. crossed-brick couplet test was used with certain modifications, such as painting the bottom brick with neat portland cement to assure the top brick being the test brick. Materials used in the test were Type I portland cement, Type S hydrated lime, a local sand, a smooth common brick with 12-30 gm. absorption and a wire-cut face brick with 10 holes, 14 gm. absorption.

In all three tests, the conventional lime-cement mortar had excellent bond strength whereas the same mortar loaded with air entrainment exhibited poor bond.

Research sponsored by the National Concrete Masonry Association[3] also showed the detrimental effect of high air content on tensile bond, as shown in Figure 5. In this graph, bond strengths are plotted against the ratio of mortar compressive strength to air content. This study revealed that the lime-cement mortars tested had air contents below 7-8% and, therefore, had better tensile bond strengths than the mortars made with masonry cements, which contained more than 13% air content. On the basis of this study, N.C.M.A. recommends an air content below 10% where a tensile bond of 75 p.s.i. minimum is desired.

S.C.P.I.[2] also recommends that air content be held to a minimum for maximum bond strength. For this reason the Institute prefers lime-cement mortars over limestone-based masonry cement mortars, which normally contain excessive amounts of air entrainment. Explanation of the poor bond strength of high air entrained mortar lies in the myriad of microscopic air bubbles at the bond plane which prevent intimate contact.

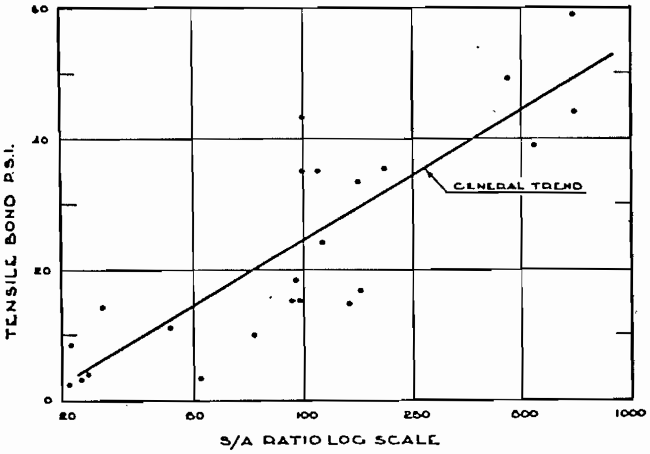
Workmanship—Tensile bond strength is also influenced considerably by workmanship, particularly by the time interval between mortar laying and brick placing, filling of joints, pressure applied to the brick and mortar re-tempering. Ritchie and Davison[6] showed that the bond strength of brick panels was reduced from 70 p.s.i. to 20 p.s.i. when the interval was increased from 30 to 90 seconds; leakage through the panels also increased as the interval was increased. It was also shown that increased pressure on the brick improved tensile bond; e.g., the bricklayer-constructed panels had higher bond strength than those made by the tap of a four-pound hammer dropped 1½ in., which, in turn, were better than a two-pound hammer dropped the same distance.

The Canadian researchers also studied the effect of re-tempering, using 13 gm. suction brick and a 1:1:6 mortar; they ascertained that the bond strength decreased as the time interval before re-tempering increased; it varied from 40 p.s.i. when used immediately to 20 p.s.i. when re-tempered four hours after mixing.

It is also a well-known fact that moving or tapping the masonry unit before the mortar has begun to harden is detrimental to bond; and therefore, the units should not be shifted after placement.

Texture of Masonry Units—Obviously the roughness of the masonry unit surface has a bearing on bond strength, with the bond being less with smooth die-skin surfaces than with wire-cut or textured brick and concrete block. An important study on the relation of bond to brick surface physics was made by J. C. Thornton,[9] in which he placed great importance not only on roughness, but also on capillary action of the units. He indicated that high water retention and workability are important, particularly with rough brick, so that the mortar can flow readily into all depressions to produce an intimate contact.

Fallacy of Bond Test—The preceding section dealt with the various interrelated factors which influence tensile bond strength, as determined principally by the crossed-brick couplet test. The major-



NOTE: S = COMPRESSIVE STRENGTH of MORTAR P.S.I.
A = AIR CONTENT of MORTAR %

FIG. 5. Relation of tensile bond strength of concrete block couplets to air content of mortar. (Redmond)[3]

ity opinion of the various researchers was that maximum tensile bond strength can be obtained with high compressive strength, low air content mortar (e.g., 1:½:4½ cement, lime, sand mix), and with moderate suction masonry units.

With respect to the low lime content recommended, the above conclusion is misleading and incomplete. First, there is general agreement that the test itself is not completely reliable. J. C. Pearson,[10] in particular, pointed out the general lack of reproducibility in his 1943 A.S.T.M. paper. Other independent researchers concur in the shortcomings of the test. Apparently it has been adopted more from an expediency standpoint, since no other test has been advanced that is better.

One of the shortcomings is use of several artificial procedures which do not simulate actual field conditions. In particular, the specimens are prepared and cured meticulously in the laboratory, and, therefore, are not subjected to extremes of weather and workmanship, and of mass production techniques typical of the field. The delicate laboratory treatment actually penalizes high lime mortars more than high cement mortars, especially under hot summer conditions, when brickmasons prefer to use the former because of its better workability, higher water retention, and greater ease in filling joints completely.

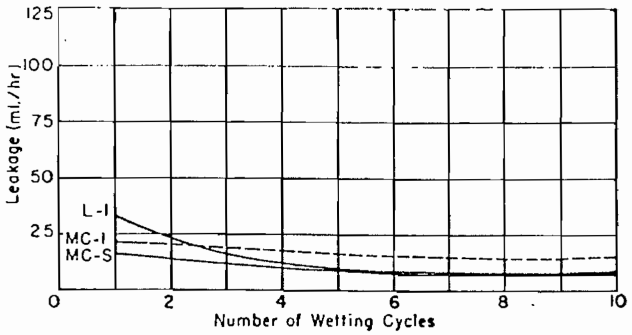
It is also erroneous to place credence on the tensile bond strength value *alone,* since it only tells part of the bond story. The other and perhaps more important part, pertains to *extent of bond* and *bond durability*—factors which determine the watertightness and durability of a wall.

EXTENT OF BOND

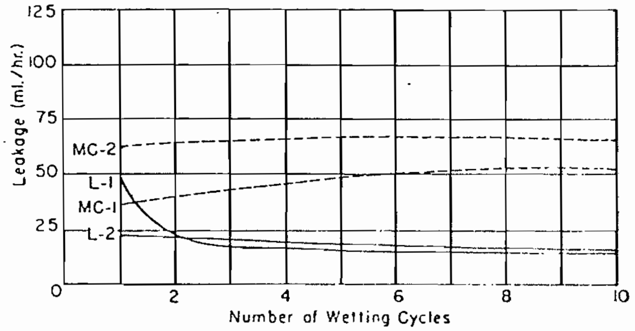
The importance of extent of bond was recognized by Palmer and Parsons[11] in the supplement to their 1934 report, where they pointed out that a stronger bond may be obtained with the weaker of two mortars (i.e., weaker in tensile bond strength) because a greater extent of bond is obtained with it and a given unit than is obtained by the stronger mortar. They defined extent of bond as the bonded area (percent of brick to which mortar adheres) divided by the bonding area.

In 1935, Palmer[12] developed the concept, "bonding efficiency", or the ratio of the tensile bond strength of brickwork (i.e., of brick couplets) to tensile strength of mortar (as determined from 1 x 4 x 12 - in. mortar slabs)—both samples cured for three months. The two key factors influencing bonding efficiency are extent of adhesion and intensity of adhesion. Palmer cited data showing that high lime mortars, because of their high degree of workability, stickiness, and high water retention, promote excellent adhesion and extent of bond, therefore, have high efficiencies. He also pointed out that the efficiency varies little with the type of brick, provided the mortar is adaptable; the inference was that high lime mortars are adaptable.

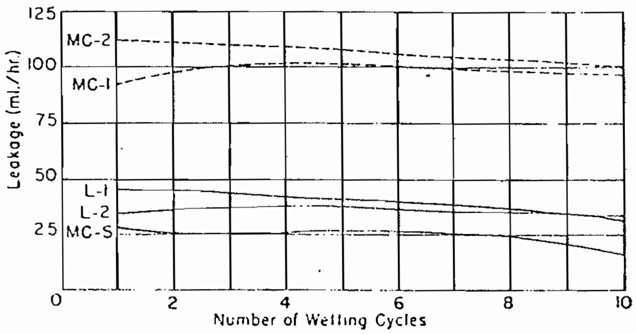
Wall Leakage Tests—It is generally recognized that in a preponderance of cases of leaky masonry walls, the leakage occurs through channels at the mortar unit-interface. Thus, high water infiltration indicates a poor extent of bond, rather than a highly permeable mortar or masonry unit. Accordingly,



A– Leakage tests for low-permeability brick.



B– Leakage tests for medium-permeability brick.



C– Leakage tests for high-permeability brick.

FIG. 6. Relation of brick permeability to mortar type in wall leakage test. (Minnick).[14] L-1 is 1:2:9 cement, lime, sand mix; L-2, 1:1:6; MC-1 and MC-2 are 1:3 masonry cement-sand mortars, both brands containing no lime; and MC-S is a 1:3 special masonry cement-sand mortar, the cement containing considerable lime.

many researchers have conducted leakage or permeability tests in the laboratory, using either wall panels or brick boxes (chimneys).

One wall permeability study was made by C. C. Fishburn,[13] involving 140 wallettes, including 39 kinds of units and 10 types of mortar. According to the report, wall leakage was low when the water retentivity of the mortar was high and brick suction low; the effect of water retentivity was especially great when the brick suction was high. Mortar having a low water retentivity stiffened rapidly when placed in contact with dry, highly absorptive brick, and units having a low suction floated out of alignment when placed in contact with such a mortar.

L. J. Minnick[14] reported another wall leakage study in 1959, involving 4-brick assemblages made with five mortar types and three kinds of brick. Figure 6 shows that in the case of the low permeability brick (A) relatively little difference is evident for the three mortars tested, although the mortars containing lime demonstrated a beneficial effect in reducing the leakage condition. The differences between mortars are more marked for brick of higher permeability (B and C). In the latter case, considerable advantage results from the use of lime in the mortar—especially after a few cycles of wetting and drying.

A comparison of the leakage results of the assemblages made with the various brick using a specific mortar indicates that the absorptions of the brick, as separate units, show little similarity to the leakage of the assemblage. This is true regardless of which type of mortar is used in the comparison.

T. Ritchie and W. G. Plewes,[15] using 3½- x 4-ft. panels in their leakage tests, found similar results with respect to lime content, as shown in Figure 7. Less leakage with the high lime mortar was attributed to the better extent of bond, which resulted from the mortar having high water retention and better workability. The bricklayer who constructed the panels commented on the importance of workability in obtaining a good bond.

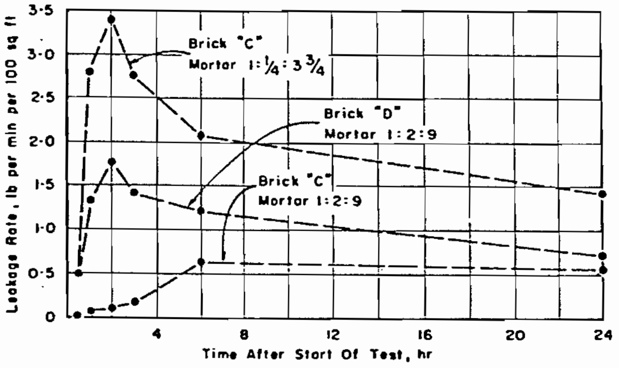


FIG. 7. Leakage rates of 8-in. panels vary with mortar and brick types (Ritchie and Plewes).[15] Brick C is a dry-press shale brick with high suction, and Brick D is a coarse concrete brick, having relatively high suction.

TABLE III. *Effect of Water Retention on Leakage*

Panel No.	Water Retention	Leakage (in ml.)*	Bond Strength (p.s.i.)
1	70.5	1030	9.5
2	70.5	1225	9.6
3	74.3	510	12.0
4	74.3	165	12.6
5	78.0	25	16.9
6	78.0	68	10.2

* Amount of water passing through panel in 24 hours.

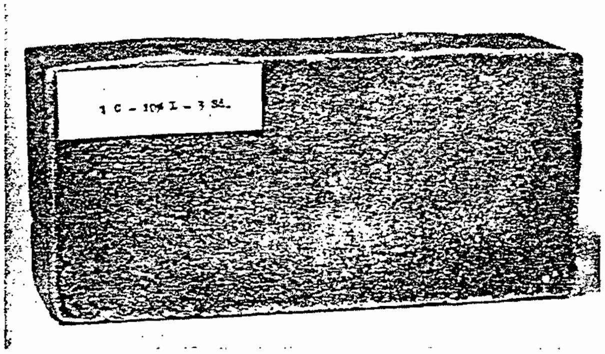
The major study by Ritchie and Davison[6] referred to earlier also involved wall leakage tests. Among the many variables affecting leakage, water retention ranked high, with leakage decreasing as water retention increased, as shown in Table III.

One of the principal contributions of the Ritchie-Davison study was the importance placed on extent of bond in connection with watertight walls. The authors remarked that a particular brick and mortar combination may have a complete extent of bond at the interface, yet have relatively low strength of bond, whereas another combination may have a "patchy", or incomplete extent of bond with the greater strength.

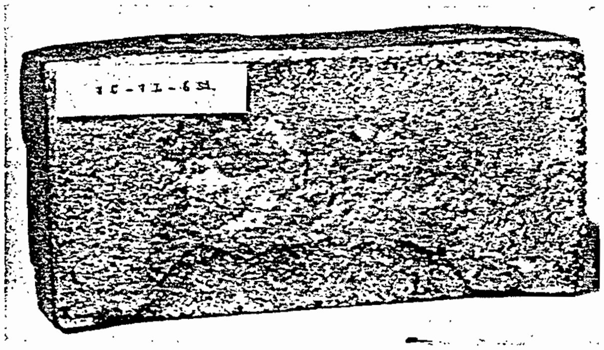
Leo Kampf,[16] City of New York, reported the use of brick boxes to measure wall permeability at the 1962 A.S.T.M. Masonry Symposium. The boxes were filled with water, and the drop in water level was measured at various intervals. It was noted that the permeability was affected by the intimacy of contact between the mortar and brick. Workability of mortar was found to be the most important factor affecting bond, because of its profound effect on workmanship. Kampf advocated high water retentivity and low suction brick for maximum watertightness.

Lime's Contribution to Extent of Bond—Because lime makes mortar highly plastic and workable and resists excessive suction, masons using high lime mortars can fill joints completely with relative ease. Lime's extreme fineness and plate-like structure permit the mortar to flow into minute irregularities rather than bridge across them, thereby providing a keying action; these unique characteristics also make the mortar stick readily to the masonry units. Lime's high water retentivity is also important when dense, low absorptive brick are used, since bleeding, which would produce a weak water plane at the interface, is minimized. These several attributes of lime contribute to greater extent of bond. In sharp contrast to lime, portland cement is much coarser and harsher working, and consequently produces a patchy, tentacular type of bond rather than an intimate one.

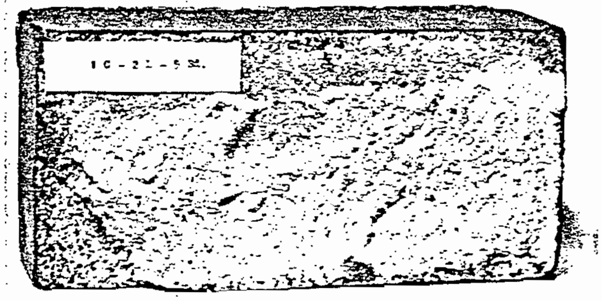
Lime's contribution to completeness of bond is illustrated in Figures 8 a, b, and c, taken from "Exterior Masonry Construction", written by the late Professor Walter C. Voss[17] of M.I.T. Figure 8a depicts the poor bond obtained from a high suction brick and low lime mortar; 8b, partial bond from a low suction brick and medium lime mortar; and, 8c, substantial bond from a high lime mortar and medium suction brick.



a—No bond from high cement mortar and high suction brick.



b—Partial bond from medium lime mortar and low suction brick.



c—Substantial bond from high lime mortar and medium suction brick.

FIG. 8. Extent of mortar bond varies with mortar and brick types (Voss).[17]

Even more striking evidence of completeness of bond are Figures 9 a, b, c, and d, which represent photomicrographs of surface and thin sections made of old mortar-brick specimens. This pioneering petrographic study was initiated during the 30's by Voss,[18] and continued by his associate, H. R. Staley.[19] (The photos are taken from Staley's 1937 paper.)

Figure 9a is a surface photo of a high-cement mortar, which appears to have made an excellent, intimate contact with the brick. However, upon examination of a thin section of the same specimen, at 60x magnification, it is apparent that voids are present at the interface, with ample evidence of considerable earlier water passage. In contrast, Figure 9c shows a 1:2:7 mortar which exhibits excellent contact in spite of the rough brick surface. An even more dramatic illustration showing the contrast in influence of mortar types on bond is Figure 9d, which represents a surface photo of the preceding specimen, taken at the juncture of the old high lime mortar (O.M.) and the new high cement-pointing mortar (P.M.) which is about $\frac{3}{8}$ in. deep. The old lime mortar still retains the same intimate contact, whereas the cement mortar has cracked loose from the brick. Staley noted upon visual inspection that water had penetrated up to the lime mortar, and no further.

From this study he concluded that:

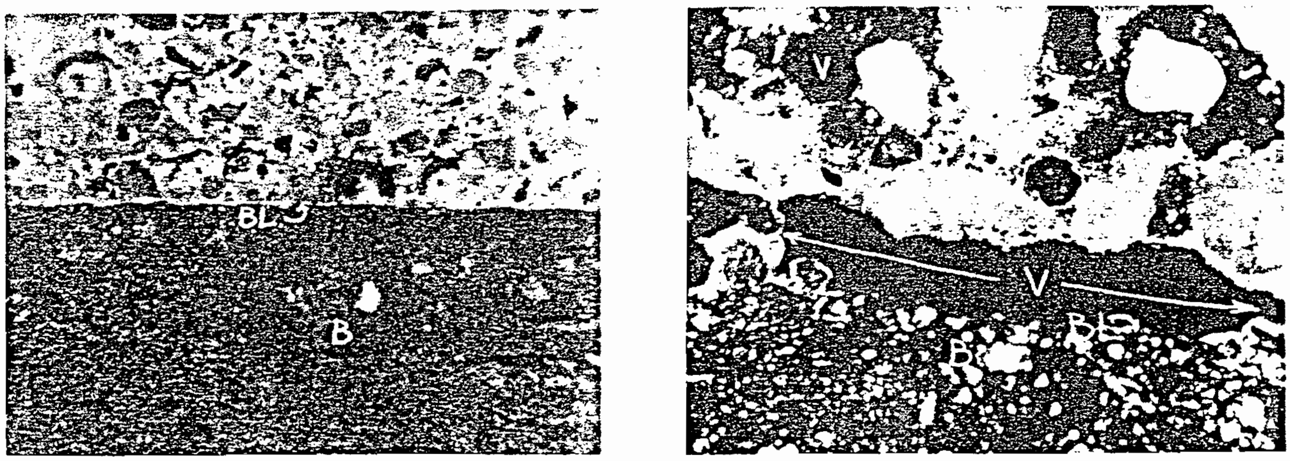
1. Intimacy, continuity, and permanence of interfacial bond are necessary for watertightness of walls.

2. Low lime mortars give a tentacular type of contact which is neither continuous nor makes a permanent bond, whereas high lime mortars give an intimate, continuous and permanent bond with brick.

BOND DURABILITY

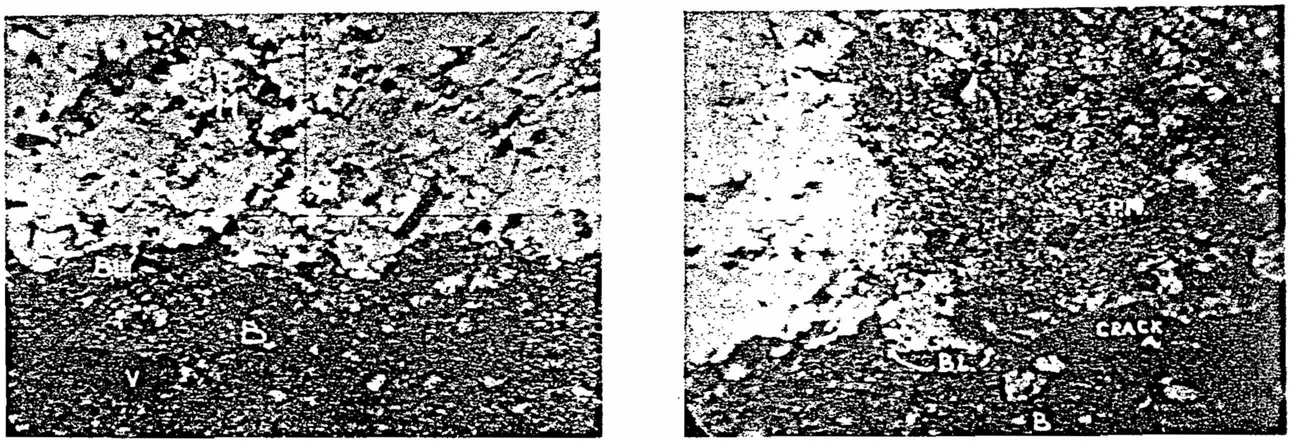
A discussion of bond would not be complete without consideration of *durability of bond,* which is of equal importance to tensile bond strength and extent of bond. Should separation cracks develop during and after hardening, the wall becomes subject to water penetration, and ultimately may fail.

Here again high lime mortars have a distinct advantage over high cement mortars, since they are not subject to the degree of cracking (particularly separation cracking) as the stronger, more rigid mortars. This cracking may occur during initial



a. Surface photo of high cement mortar, age 21 years, reflected light, 20x magnification, shows apparent good bond of mortar to brick.

b. Thin section of same specimen in (a), photographed in transmitted light, crossed nichols, 60x magnification, shows incomplete bond.



c. Surface photo of 1:2:7 cement, lime, sand mortar (age 37 years) which exhibits good contact in spite of rough brick surface (reflected light, 20x magnification).

d. Surface photo of same specimen in (c), 20x magnification, showing intimate contact of old mortar (OM) in contrast to incomplete bond of cement pointing mortar (PM).

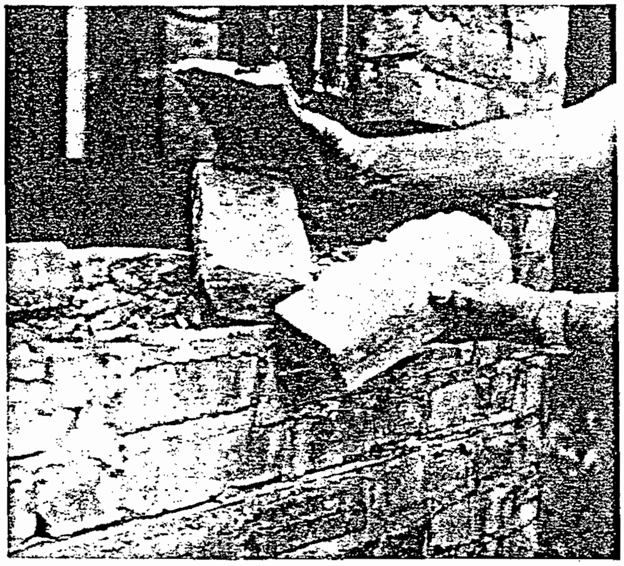
FIG. 9. Photomicrographs of old mortar-brick specimens show variation in extent of bond and bond durability (Staley).[19] B, Brick; M, Mortar; V, Void; BL, Brick Line; OM, Old Mortar; and PM, Pointing Mortar.

hardening, as a result of shrinkage and compaction of the mortar, or subsequent to hardening, due to cyclical volume changes (wetting and drying) and/or wall movement.

Palmer[20] and Staley[21] felt that volume change occurring subsequent to hardening was the major cause of separation cracking, particularly when the extent of bond was poor. Since high cement mortars exhibit the greatest cyclical volume change among mortar types,[21] and also provide the poorest extent of bond, they concluded that these mortars do not promote *durable bond.*

Voss[17] also emphasized that high lime mortars were slow hardening and remained elastic or flexible, and therefore, were able to accommodate stresses caused by building movement and cyclical volume changes without excessive cracking. These mortars also possessed greater adhesive (bond) strength than cohesive (internal) strength; thus, if cracks developed, they would most likely occur within the mortar joint itself rather than at the interface, where leakage would be more of a problem.

Minnick[14] proved lime's greater elasticity in his 1959 study involving sawed four-brick assemblages. He concluded that the presence of lime in mortar increased the bond and formed well-integrated assemblages with relatively high values of Young's modulus of elasticity, good flexural strengths, and a tendency to break under load within the mortar itself rather than at the bond. In contrast, the assemblages made with lime-free mortars, i.e., lime-



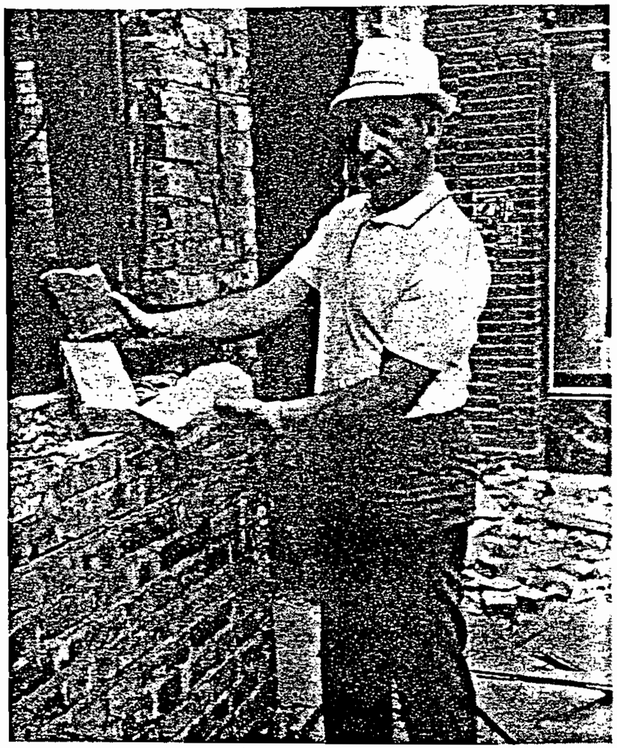


FIG. 10. Wrecking contractor holds sample of old brick-lime mortar from original building in left hand, and backup brick-high cement mortar from modern store front in right hand. Close-up shows intimate contact of old lime mortar, whereas the high cement mortar (held in hand) has "pancaked", breaking clean from the brick.

stone-based masonry cements, tended to break at the interface and generally demonstrated lower flexural strength. Many of the masonry cement specimens even fell apart at the bond during handling.

Another important aspect of bond durability is autogeneous healing or the ability of lime-based mortars to heal minute cracks or fill minute voids in the mortar joints. This reconstitution of mortar, which helps make walls watertight, is explained by the recarbonation of the lime following cycles of wetting and drying. (See NLA Technical Note #1 on Durability.)

Empirical Evidence—A major contribution relating to the subject of bond durability was C. C. Conner's[22] 1948 A.S.T.M. paper, which was based upon a close examination of 100 New Jersey Bell Telephone masonry buildings six to 23 years in age. Fifty-four of them were watertight, and 46 leaked in varying degrees. The key factor characteristic of the watertight buildings was the use of a workable, high water retentive mortar which exhibited no (or very little) cracking (1:1:5-6 and 1:2:7½ cement, lime, sand mixes). In contrast, the leaky structures, built mainly with high cement mortars, showed extensive separation cracking (the minimum was 26 ft. of cracking per 100 ft. of mortar joints); one structure, made with a high cement mortar and low suction brick, had 68 ft. of cracks per 100 ft. of joints, only five years after construction. Other factors contributing to watertight walls noted by Conner were the use of moderate suction brick and concave tooled joints.

Demolition work provides more evidence of bond durability, as pointed out by Conner.[23] Where joint cracking and wall leakage are prevalent, the brick rubble invariably shows a wide variation in extent of bond. In contrast, walls made with moderate suction brick and high lime mortar exhibit excellent extent of bond and a minimum of cracking, thereby making the wrecking and brick salvage operations difficult and costly. Wrecking contractors actually dread the latter type walls, and this reflects in their higher bid costs for demolition.

Figure 10 shows a demolition project in Washington, D.C. of a 19th century brick building made with straight lime mortar, but having a modern store front made with a high cement mortar. Brick from the store front was salvaged readily because the mortar had "pancaked", and it could be loosened from the brick with a gentle tap; in contrast, the lime mortar from the original building was bonded strongly to the brick, and considerable effort was needed to clean the units.

CONCLUSION

A summary of the major points of this discussion is given in Table IV, which compares various mortar types as relating to several aspects of bond. Note that the high lime mortar (1:2:9) is considered to have low bond strength, yet high extent of bond

TABLE IV

ASTM Mortar Type	Water Retention	Tensile Bond Strength	Extent of Bond	Bond Durability	Permeability in wall test (Leakage)
Type M or S (1:¼-½:3-4½)	Low	High	Very Low	Very Low	High
Type N (1:1:6)	High	Moderate	High	High	Low
Type O (1:2:9)	Very High	Low	Very High	Very High	Very Low
Type N (1:3) (Masonry cement with limestone and high air)	High	Very Low	Low	Moderate	High
Type N (1:3) (Masonry cement with lime and moderate air)	Very High	Low	High	High	Low

and durability; the high cement mortars are just the reverse. Mortars made with pulverized limestone and high air content generally rate poorly on all three bond factors.

This report has emphasized that the tensile bond strength test, which many researchers use solely to evaluate mortar bond, tells only part of the bond story. And this part actually is not conclusive since the test (crossed-brick couplet) is not completely reliable, and further it departs in numerous ways from actual field conditions. In essence, the test depreciates the value of lime in mortar, since it fails to take into account its greater flexibility in field use than portland cement. Consequently, for a more realistic picture of bond, more emphasis should be placed on extent of bond and bond durability, since these are the key factors which promote watertight walls and wall integrity.

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