Effect of Lime on Characteristics of Mortar in Masonry Construction

L. JOHN MINNICK

G. & W. H. Corson, Inc., Plymouth Meeting, Pa.

The investigation describes tests which were carried out with the object of developing a better understanding of the performance characteristics of brick masonry construction which have been observed in the field and for the further purpose of setting up convenient laboratory tests which could serve for evaluation of various mortar materials with brick of widely different characteristics. Five types of mortar were included in the study together with five different brick. The procedures included studies of leakage and efflorescence made on mortar-brick assemblages and measurements of integrity of the mortar-brick linkage on specimens cut from the assemblages. The presence of lime is found to be beneficial in developing less leakage, tighter bond, less efflorescence, and high mortar-brick assemblage strength.

A number of interesting investigations were reported several years ago which considered some of the factors relating to watertight characteristics of brick walls.[1] In general these studies were concerned with the use of conventional lime-cement mortars. More recently the construction industry has been employing quantities of prepared cement mixtures (masonry cements) which are made up of Portland cement, finely ground limestone, and a variety of organic admixtures. The admixtures are put into the masonry cement to improve workability and also to entrain quantities of air in the mortars—thereby improving resistance to freezing and thawing. Since practically all of the prepared masonry cements do not contain hydrated lime, it is evident that additional information is needed relating to the properties of these cements in brick structures, particularly as compared with the conventional lime-cement mortars. Furthermore, it is desirable to consider the effect of the use of hydrated lime in prepared masonry cements on the performance characteristics of the mortar-brick assemblage.

The study which is reported here was carried out to extend our knowledge of the performance of these masonry materials in the field. The laboratory tests were designed to evaluate the various mortar materials in combination with several types of commercially available brick. The investigation has reached a point where it was felt desirable to prepare this report, although it is to be pointed out that the studies are by no means complete. It is hoped that as additional results become available subsequent reports can be made.

Materials Used in the Investigation

Hydrated Lime. The hydrated lime employed in the tests was primarily a Type S (ASTM Designation: C 206) material as commercially produced by G. & W. H. Corson, Inc.[2] In some of the tests, however, a composite material was used made up of both high calcium and dolomitic limes, Type S, from four separate sources of supply. Table I gives the characteristics of the lime.

Portland Cement. The Portland cement consisted of three brands of commercially available Type I materials which were prepared as a composite mix. Some of the mortar was also prepared from a single brand of cement. Table I gives the characteristics of the cements.

Masonry Cemetn. Three well-known commercial brands of masonry cement were selected for this investigation. Sample bags were procured from the open market. Two of these masonry cements do not contain lime. The third blend contains a substantial amount of Type S hydrated lime in its formulation (35% by volume). The characteristics of these materials are included in Table I. These masonry cements all conform with the requirements of ASTM Designation: C 91.

Sand. A typical mortar sand that is widely used in the Philadelphia area was employed. The characteristics of this sand are given in Table II. In addition, a standard graded Ottawa sand was used, conforming to the grading given by ASTM Designation: C 109.

Brick. Five different types of brick were employed in the investigation. Their characteristics are given in Table III.

Testing Procedures

Mortar Mixes. The mortars which were prepared for the tests were mixed in a mortar mixer in accordance with ASTM Designation: C 109. The mixes are given in Table IV. The preparations used are the same as normally employed in field practice.

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[1] (*a*) J. W. McBurney, M. A. Copeland, and R. C. Brink, "Permeability of Brick-Mortar Assemblages," *Proc. Am. Soc. Testing Materials*, **46**, 1333–48 (1946).

(*b*) C. C. Fishburn, D. Watstein, and D. E. Parsons, "Water Permeability of Masonry Walls," BMS7, U. S. Govt. Printing Office, October 8, 1938.

(*c*) C. C. Fishburn, "Water Permeability of Walls Built of Masonry Units," BMS82, U. S. Govt. Printing Office, April 15, 1942.

(*d*) L. A. Palmer and D. E. Parsons, "Permeability Tests of 8-in. Brick Wallettes," *Proc. Am. Soc. Testing Materials*, **34**, Part II, 419–31 (1934).

(*e*) F. O. Anderegg, "Some Properties of Mortars in Masonry," *Proc. Am. Soc. Testing Materials*, **40**, Part II, 1137–41 (1940).

(*f*) C. C. Fishburn, D. E. Parsons, and P. H. Petersen, "Effect of Outdoor Exposure on the Water Permeability of Masonry Walls," BMS76, U. S. Govt. Printing Office, August 15, 1941.

[2] (*a*) B. L. Corson, "Dry Lime Hydrate and Process for Producing Same," U. S. Pat. 2,309,168, January 26, 1943; Can Pat., 412,325, May 4, 1943.

(*b*) B. L. Corson, "Methods of Conditioning and Treating Lime and Product Thereof," U. S. Pat. 2,409,546, October 15, 1946.

Table I.

Characteristics of Limes

	Type S[a] (Corson)	Type S[a] (composite)
Plasticity	415	365
Popping and pitting	None	None
Residue:		
Retained on a No. 30 Sieve (%)	0.08	0.12
Retained on a No. 200 Sieve (%)	4.42	4.60
Weight per cu. ft. (lb.)	50	50

Characteristics of Cements

	Portland[b]		Masonry[c]		
	Single brand	Composite	MC-1	MC-2	MC-S
Fineness:					
Specific surface (Wagner)	1745	1772			
Residue on #325 sieve (%)			2.26	8.81	4.8
Soundness, autoclave expansion (%)	0.341	0.307	0.08	0.04	0.09
Time of setting (Gillmore):					
Initial	2:45	2:20	6:30	2:45	4:15
Final	4:45	5:20	8:30	7:30	7:05
Air content (%)	6.1	4.9	15.0	21.8	20.6
Water retention (%)			70.4	69.4	82.4
Weight per cu. ft. (lb.)	94	94	70	70	70
Compressive strength (average of 3 cubes)					
1 day	908				
3 days	2267	2278			
7 days	3522	3446	1038	1105	875
28 days	5250	5057	1535	1414	1554

[a] Methods of test as included in ASTM Designation: C 110.
[b] Methods of test as included in ASTM Designation: C 150.
[c] Methods of test as included in ASTM Designation: C 91.

Mortar-Brick Leakage Tests. The recent studies of Thornton[3] and Ritchie[4] have re-established the importance of the development of suitable laboratory testing procedures which will evaluate the leakage of water through a mortar-brick assemblage. These investigators have indicated the importance of determining the effect on leakage that is caused by brick differing in porosity and surface texture and also the effect caused by variation of the mortar composition. At the start of the present investigation some preliminary trials demonstrated that the leakage of assemblages made with various brick, using either high-lime or high-cement mortars, had substantially no correlation or similarity to the porosity or absorption of the brick measured as separate units. Furthermore, assemblages made up using asphaltic cement as the mortar joint have shown that moisture transfer occurring along the surface of the asphaltic bonded brick is quite different from the transfer that develops when lime or Portland cement mortars are employed. It was indicated that the presence of water soluble components in mortar-brick assemblages very materially affected the transfer of moisture, particularly after a few cycles of wetting and drying. Hydrated lime, bicarbonates, alkalies from Portland cement are examples of salts that have some solubility and therefore can be expected to develop migrating ions during periods of wetting and drying. This migration of salts causes plugging effects in the case of the lime and is a possible source of efflorescence in the case of the soluble alkalies. The compounds which are redeposited in the pores of the brick induce a diminishing effect on the water permeability of the brick and mortar.

In view of these observations and for the further purpose of establishing tests which would more closely simulate field conditions, the investigation was based on tests in which the total "leakage of water" would be established through mortar-brick assemblages. This procedure has the advantage that no adjustment is required for the independent permeability of either the brick or the mortar as such. A four brick assemblage is prepared using $^1/_2$ in. joints tooled on all edges. Moisture content of the brick at the time of preparation of the specimens was varied from dry to saturated. Figure 1 illustrates the assemblage used in this test. A metal backing container is fastened with a bituminous cement after the specimens had first received preliminary curing of 28 days in a moist closet at 95% humidity.

Table II. Characteristics of Commercial Mortar Sand

Tested in accordance with ASTM Designation: C 144.
Sieve analysis:

Screen	Passing, %
4	100.0
8	99.8
16	96.1
30	71.2
50	26.2
100	3.3

Amount of material finer than No. 200 sieve: 1.23%
Organic impurities: Sand suitable for use in mortar
Fineness modulus: 2.03.
Weight per cu. ft. surface dry condition: 80 lb.
Soundness test of fine aggregate ($MgSO_4$):

	Weight		
Screen	Before	After	Passing finer sieve, %
30	100	99.0	1.0
50	100	99.6	0.4

NOTE: Aggregate was subjected to five cycles as specified.

After placing the metal backing on the assemblage, sufficient water is added to bring the level even with the top of the assemblage. The rate at which this water level drops is observed and recorded during a period of 24 hours. At this time interval, the water in the tank is dumped out and the assemblage allowed to stand in the laboratory air until it reaches constant weight. This drying procedure normally requires about three days. At this point the container is again filled with water and the entire procedure repeated. Measurements are taken of the rate of total water dissipation

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[3] J. C. Thornton, "Relation Between Bond and the Surface Physics of Masonry Units," *J. Am. Ceram. Soc.*, 36 [4] 105–20 (1953).

[4] T. Ritchie, "Study of Efflorescence on Experimental Brickwork Piers" and "Study of Efflorescence Produced on Ceramic Wicks by Masonry Mortars," *J. Am. Ceram. Soc.*, 38 [10] 357–66 (1955).

Table III. Brick Characteristics

Brick designation	Type brick	E[a], p.s.i. × 10^6	Compressive strength,[b] p.s.i.	% Absorption[b] 24 hr. soak	Initial rate of absorption,[c] g./min.	Permeability[d] in. drop/15 hr.	Suction rate,[e] g./min.	Surface rise,[f] in./15 min.
A	Hard shale, smooth finish	32.2	9047+	4.4			11.8	0.7
B	Hard shale, smooth finish	18.2	6487	9.9	38.4	7.6	20.4	2.7
C	Soft mud, sand finish	16.7	2480	6.2	33.5	10.0	28.8	8.1[g]
D	Stiff mud—end cut, smooth finish	6.6	887	12.5	79.3	7.5	25.2	7.7
E	Stiff mud—end cut, smooth finish	12.8	1269	19.1	40.1	2.1	32.9	2.3

[a] Dynamic Young's Modulus of Elasticity.

[b] Tested in accordance with ASTM Designation: C 67.

[c] Tested in accordance with applicable portions of ASTM Designation: C 67 except that the brick is placed face side down instead of flat side down in the water.

[d] Measured as drop in head of water from initial head of 10 in. through face of brick.

[e] Determined on brick specimens placed on end in $^5/_8$ in. of water. Rate averaged over a five minute period. ASTM Designation: C 67.

[f] For method of test refer to Section III of "Relation Between Bond and Surface Physics of Masonry Units" by John C. Thornton.

[g] Climbed entire length of brick (8.06 in.) in less than 15 minutes.

Table IV. Mortar Proportions and Characteristics

Mix designation	Proportion in parts by volume				Young's Modulus of Elasticity[f]		Compressive strength, p.s.i.—28 days[h]
	Portland cement[a]	Lime[b]	Masonry cement	Sand[c]	Type cure[g]	E (p.s.i. × 10^5)	
L-1	1	2	0	9	Air	14.5	
					Moist	15.5	758
L-2	1	1	0	6	Air	22.2	
					Moist	26.3	1512
MC-1	0	0	1[d]	3	Air	19.5	
					Moist	25.8	1535
MC-2	0	0	1[d]	3	Air	16.6	
					Moist	18.2	1414
MC-S	0	0	1[e]	3	Air	16.0	
					Moist	20.6	1554

[a] A composite material made up of three different brands of Type I Portland cement.

[b] A composite material made up of four brands of Type S hydrated lime.

[c] Graded Ottawa or commercial mortar sand as indicated in text and tables.

[d] Commercial masonry cements—no lime present.

[e] Special masonry cement—contains lime.

[f] Determined on $1^1/_4$ x 2 x 8 in. beams made with Ottawa sand.

[g] Air storage—70°F.; Relative Humidity 50–60%. Moist storage—70°F.; Relative Humidity 95%

[h] Average of five or more cubes 2 x 2 x 2 in., moist cured.

through the mortar-brick assemblage specimen for each wetting cycle. The total leakage is then calculated as the average number of milliliters of water lost through the assemblage per unit of time (one hour). In addition, leakage of water through the assemblage is visually observed and the character of the leak noted.

Photographs are taken of the mortar-brick assemblages at each cycle so that a complete record is available showing the rate of growth of efflorescence. A few of these photographs are included in this report.

Mortar-Brick Linkage Strength. It is recognized that the integrity of the mortar-brick assemblage can only be established indirectly when physical measurements are made on the mortar or the brick alone, and measurements on the separate components may at times actually give misleading information as far as performance of a wall or structure is concerned. The procedure which has been adopted, therefore, for these tests consists of preparing mortar-brick assemblages as described for the leakage tests, and after 28 days sawing out sections from these assemblages with a diamond saw. The use of the sawed sections has been

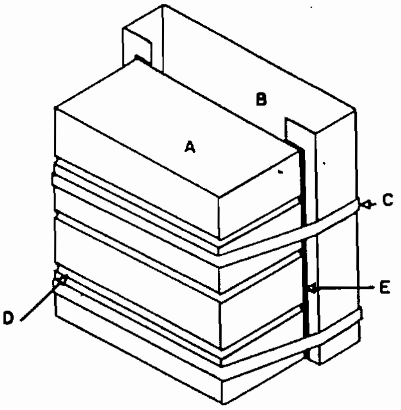

Fig. 1. Schematic drawing showing arrangement of metal backing as applied to mortar-brick assemblage. (A) Brick-mortar assemblage, (B) galvanized metal backing container, 2 by 9 by 11 in. with capacity of 3000 ml., (C) galvanized metal strap, (D) mortar joint, and (E) bituminous sealing compound.

adopted in order to avoid variations which can occur at the outer surface of the joints due to tooling. Also the specimens are equivalent in size to those employed in a separate research study on these materials.[5] Figure 2 is a photograph of a few of these sections. Sizes range from $^1/_2$ to $1^1/_4$ in. in thickness and are 2 in. wide and from 10 to 11 in. in length.

The diamond saw was adopted after considerable experimentation since it is realized that sawing out sections could easily produce strains in the specimens which might impair the reliability of the test. The diamond tipped wheel permitted the operator to cut the assemblages with relative ease, with a high degree of precision, and with virtually no evidence of shock or stress at the mortar joints. Therefore it is felt that the technique evolved can be easily carried out with the standard type Clipper saw modified as indicated.

Two methods have been used in curing the specimens. The first consists of curing the uncut assemblages for 28 days in a manner analogous to that employed in the previously described leakage tests. At 28 days the assemblages are cut into sections and the newly prepared specimens are then returned to the curing room for additional aging under the same storage conditions used for the uncut assemblages. The second method consists of alternately wetting and drying the uncut assemblages by means of a water spray, the drying being carried out in the laboratory air for 3 days. As before, the assemblages are cut into sections at 28 days after which the sawed sections continue to receive the wetting and drying treatment until the time of test.

The cut sections are tested for fundamental transverse frequency and, in a number of cases, for flexural strength using a convention center point loading arrangement. The dynamic Young's modulus of elasticity is then determined using ASTM Designation: C 215. Where the specimens are broken in flexure the type of failure is felt to be of considerable importance; this is reported either as failure within the mortar itself or as a failure in bond. In those cases where the fracture at the bond is not completely clean, the fractional area of the face which shows adhesion to mortar is indicated.

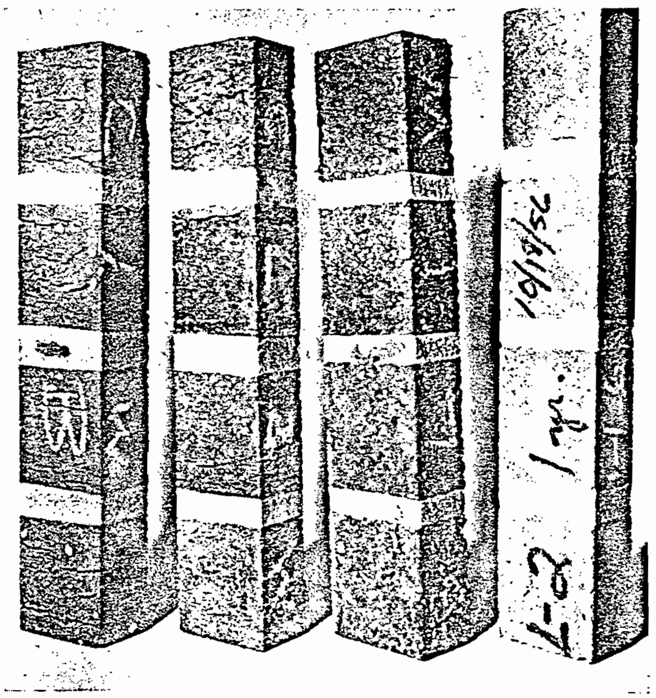

Fig. 2. Typical mortar-brick specimens as sawed out of complete assemblages.

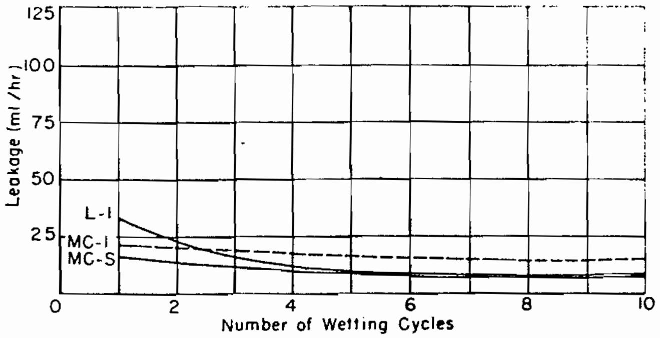

Fig. 3. Leakage tests for low-permeability brick.

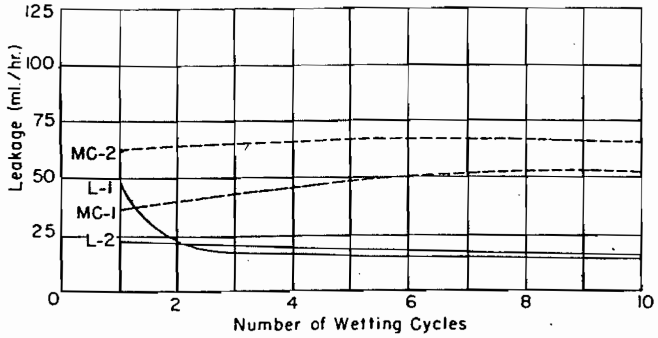

Fig. 4. Leakage tests for medium-permeability brick.

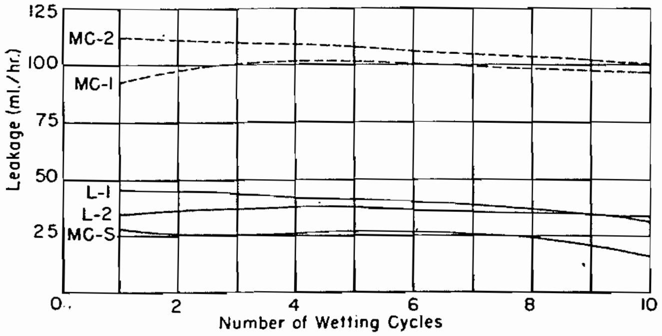

Fig. 5. Leakage tests for high-permeability brick.

Test Results and Discussion

Mortar-Brick Leakage Tests. In order to simplify the presentation the results of the mortar-brick leakage tests are presented in graphical form. Figures 3, 4, and 5 give data which are representative of the results obtained. Each figure is based on average values obtained with one type of brick and the differences between the curves on each graph reflect the differences in leakage condition caused by changing the mortar composition.

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 cases 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 with the brick characteristics given in Table III 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.

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[5] The Franklin Institute Laboratories, Philadelphia, Pa. Research project conducted for the National Lime Assn., to be reported at a later date by the Franklin Institute.

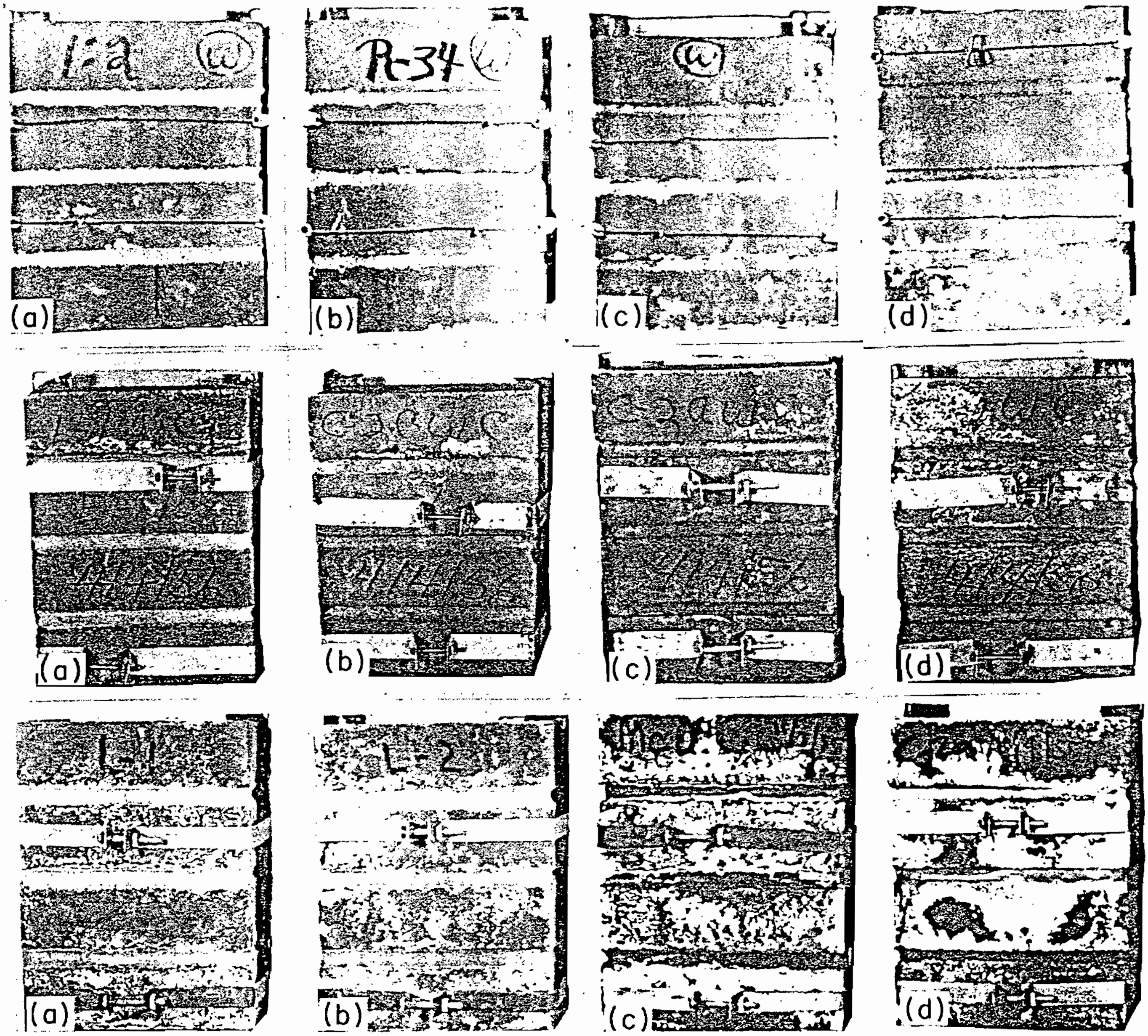

Fig. 6. Effect of leakage on efflorescence of mortar-brick assemblages after 10 cycles of wetting and drying.

Top Row: Low-permeability, low efflorescing brick. (a) high lime mortar, (b) masonry cement mortar containing lime, (c) masonry cement mortar, and (d) same as (c) but laid up dry.

Center Row: Medium-permeability, low efflorescing brick. (a) high-lime mortar, (b) masonry cement containing lime, and (c) and (d) masonry cement mortars.

Bottom Row: Medium-permeability, high-efflorescing brick. (a) and (b) High-lime mortars and (c) and (d) masonry cement mortars.

Permeability, suction rate, and capillary surface rise show a reasonably good correlation with the leakage results. Previously Thornton[3] showed that the capillary surface rise had a significant bearing on leakage through brick chimneys.

The data show that the differences in degree of leakage do not level off until after the first wet-dry cycle. Thornton's investigation did not show the differences in mortar probably because he did not consider the problem from the standpoint of alternate wetting and drying. Thornton did show a reduction in leakage at the joints when his brick chimneys were subjected to a second leakage test 15 days after his first test.

Efforts to adjust (or correct) the total leakage value for the amount of water passing through the brick, when measured apart from the assemblage, have shown in virtually every case that more water is lost through individual brick units than can be accounted for as total water lost through the assemblage. This observation substantiates the approach that leakage measurements should be made on assemblages rather than on the mortar and brick components alone.

It is evident that the leakage is generally more severe on the lower joints since these are exposed to the highest water pressure. Visual comparison of the specimens can be made at the different joints to establish the effect of the head of water on the leakage condition. This is shown in the photographs of the assemblages, Fig. 6. For most of the tests the drop in the water level did not reach a point where the upper joint was uncovered. The time of exposure therefore of all the joints to water was the same. In the few cases where the leakage rate was excessive, the rate determinations were established prior to the time that the water level dropped to the first joint.

The variation in leakage is greater when the brick are laid up in dry condition, although the variation becomes less pronounced with increased wetting and drying cycles. Most of the tests reported here have been made on assemblages laid up under wet conditions in order to make fair comparisons with the best construction procedures used with these brick.

Tests show that the variation in sand, which may be noted by comparing the results of the tests as presented in Table V.

Table V. Comparison of Leakage Rates with Different Sands

Cycle	Difference in rates of total leakage between MC-1 and L-1 mortars in ml./hr.	
	Ottawa Sand	Commercial Sand
1	+6	−7
2	+10	+10
3	+11	+12
4	+11	+11
5	+12	+10
6	+12	+9
7	+12	+7
8	+12	+6
9	+12	+7

does not appreciably influence the leakage results. These data which were obtained with a single type of brick show the difference in per cent of total leakage between the MC-1 and the L-1 mortar. Except for the first cycle in which the lime mortar showed a higher leakage with the commercial sand, the results are quite analogous for the two sands used in the tests, and the masonry cement mortar shows consistently higher leakage values.

A number of the assemblages developed efflorescence during the tests. The photographs given in Fig. 6 illustrate the extent and effect of different leakage conditions on the efflorescence. In general it was found that this condition was more prevalent with those assemblages which were made from brick which, when tested by themselves, showed efflorescence. The results did not indicate that efflorescence was primarily related to either the porosity or the permeability of the brick.

The investigation demonstrated that the *degree of leakage* materially affects the efflorescence that may be developed in a structural building assemblage. In nearly all instances the lime mortars showed the least amount of efflorescence. These results agree with those reported previously by Ritchie.[4] It is to be pointed out that the same Portland cement was used in the specimens employed for the efflorescence tests.

It is felt that the method used in the present investigation possesses the advantage of indicating by laboratory tests what can be expected for specific mortar-brick combinations that may be contemplated for field use. Where the exact field materials are not known the results indicated that it is desirable to consider using a high lime mortar since this type mortar can be expected to reduce both the tendency for leakage at the joints and the degree of efflorescence.

Mortar-Brick Linkage Strength Tests. The results of fundamental transverse frequency tests are given in Table VI as Young's modulus of elasticity. The results of Young's modulus for the brick alone and the mortar bars are included in Tables III and IV. With regard to the "E" values determined for the brick, it is noted that the values vary fairly substantially for the different series. The modulus is not related to either per cent absorption, suction rate, or permeability of the brick. The variations are undoubtedly due to the degree with which the brick have been vitrified in the kiln. This is borne out by comparing the compressive strengths and the "E" values in Table III.

The straight mortar specimens (Table IV), as expected, show higher "E" values for the mixes which are higher in Portland cement content. (L-2 is greater than L-1.) When the mortars are used in the brick assemblages the results follow a different pattern. In general, the results obtained are intermediate between the values obtained for the brick and mortar specimens measured separately. It is to be remembered that the tests were made on specimens which were cut from the assemblages at 28 days, and in each series the subsequent curing conditions were the same for the cut sections as for the assemblages. The age given is the total age of the specimen at the time of test.

No attempt is made here to evaluate the relationships between the elasticity characteristics of the individual components of the assemblages and the assemblages themselves. It is obvious that the brick occupies a greater part of the specimen volume and therefore should be the controlling element. However, structural weaknesses in the brick, effects of bond characteristics, degree of compaction during formation, discontinuities in the specimens, etc., all affect the resonance of the specimen. The significant point that can be made is that the assemblages do act as structurally integrated resonating beams, especially for those specimens which contain the lime mortar. The L-1 mortar gives somewhat higher "E" values than the MC mortar which is lower in lime content for two or the brick assemblages as indicated in Table VI. The assemblages which contained the commercial masonry cements which did not contain lime were very sensitive to handling and in many instances fell apart at the interface between the brick and mortar. For these particular specimens the assemblage could not be considered to be a structurally integrated member and Young's modulus was non-determinable. It is for this reason that Table VI does not include "E" values for some of the masonry cement-brick combinations.

In general, the data indicate that slightly higher values for "E" are obtained with the specimens that have been cured under constant humidity conditions. However, the differences that are noted on the table are within the over-all differences obtained due to variations in experimental results and therefore may not be significant.

Table VI also gives the results of some of the tests which were run on sections that were broken using the center point loading procedure. The table includes data on specimens whose total ages were 35 days. In addition, some information is available, at the time of preparation of this report, at extended ages. These data are also included in the table. It is to be noted that for the high lime mixes the break tends to occur within the mortar rather than at the bond between the brick and mortar. This fact probably explains why the assemblage strength is improved with the lime-rich mortars. The development of a higher bond between the mortar and the brick unquestionably enhances the over-all strength. In a number of instances the specimens broke through the brick. This was usually caused by a defect in the brick such as a lamination or other structural imperfection. As mentioned previously, many of the masonry cement specimens fell apart at the bond in handling and could not be subjected to the test. In most instances the lime mortars held together satisfactorily.

It is observed that the number of brick segments in the sawed sections used in carrying out the tests for fundamental transverse frequency and for flexural strength has a significant effect on the results. In general the test values are higher for a 2 unit assemblage than they are for the 4 unit specimens.

The data given in Table VI are limited to specimens made with graded Ottawa sand. A number of tests were also run with specimens made with commercial sand. The results of the test with commercial sand were essentially the same as those reported.

It is felt that the proper evaluation of mortar strength for use in unit masonry construction should be accomplished by means of tests on assemblage structures such as have been used rather than by measurements on the individual components. It is indicated that under stress there are higher energy or Coulomb friction losses developed in high-lime mortars than in straight cement mortars. This results in a beneficial "cushioning" effect under stress or an improved elasticity of the lime-rich mortars. The resiliency of the lime mortars can explain in part the relatively high strength results that have been observed for the assemblage made up with lime mortars. Thus, the idea that lime mortars are

Table VI. Tests on Mortar-Brick Assemblages Using Graded Ottawa Sand

Mortar designation	Brick designation	Absorption of brick (%)	Age (days)	Number of brick in test section	E (p.s.i. × 10^5)	Flexural strength (p.s.i.)	Description of failure
			Cured under constant humidity conditions				
L-1	B	9.9	35	4	3.5	50	100% in mortar
L-1	"	"	"	2	8.7	115	100% in mortar
MC-2	"	"	"			[a]	See footnote
L-2	"	"	"	4	4.5	[a]	See footnote
MC-S	"	"	"	"	5.2	[a]	See footnote
L-1	C	6.2	"	4	4.1	45	40% in mortar, 60% in brick
L-1	"	"	"	2		65	100% in mortar
MC-2	"	"	"	"		72	At bond
L-1	D	12.5	"	4	12.6	58	In brick
L-1	"	"	"	2	7.6	36	In brick
MC-2	"	"	"			[a]	See footnote
L-1	E	19.1	"	4	9.0	77	In brick
L-1	"	"	"	"	6.0	97	25% mortar, 75% brick
MC-2	"	"	"			[a]	See footnote
L-1	A	4.4	90	2		324	In mortar
L-1	"	"	"	"		396	In mortar
L-2	"	"	"	"		207	At bond
L-2	"	"	"	"		435	At bond
MC-1	"	"	"	"		323	At bond
MC-2	"	"	"	"		328	At bond
			Cyclic wetting and drying cure				
L-1	B	9.9	35	4		[a]	See footnote
L-1	"	"	"	2		75	100% in mortar
L-1	"	"	"	"		105	100% in mortar
L-2	"	"	"	"	6.0	[b]	See footnote
MC-1	"	"	"			[b]	See footnote
MC-2	"	"	"			[a]	See footnote
MC-S	"	"	"	4	9.0	[b]	See footnote
L-1	C	6.2	"	4	3.5	65	100% in mortar
L-1	"	"	"	2	5.1	75	20% in mortar, 80% at bond
L-2	"	"	"	"	2.8	261	25% in brick, 75% at bond
L-2	"	"	"	4	6.3	310	At bond
MC-1	"	"	"	2	4.4	[a]	See footnote
MC-2	"	"	"	"		35	100% at bond
MC-2	"	"	"	"		35	100% at bond
MC-S	"	"	"	"	4.4	[b]	See footnote
L-1	D	12.5	"	4	10.4	[b]	See footnote
L-2	"	"	"	"	4.6	58	In brick
L-2	"	"	"	"	8.9	77	In brick
MC-1	"	"	"	"	7.6	97	At bond
MC-1	"	"	"	"	5.3	88	In brick
MC-2	"	"	"	"		78	At bond
MC-S	"	"	"	2	10.9	123	50% in mortar, 50% at bond
MC-S	"	"	"	4	16.3	155	In brick
L-1	E	19.1	"	4	8.7	58	In brick
L-2	"	"	"	"	6.8	77	In brick
L-2	"	"	"	2	9.5	122	In brick
MC-1	"	"	"			[a]	See footnote
MC-2	"	"	"			[a]	See footnote
MC-2	"	"	"	4	8.9	[b]	See footnote
L-1	A	4.4	125	2		203	In mortar
L-2	"	"	139	"		300	25% in mortar, 75% at bond
L-2	"	"	"	"		300	15% in mortar, 85% at bond
MC-2	"	"	125	"		300	At bond

[a] Specimens for flexural strength test failed in handling—separated at bond.
[b] Specimens for flexural strength test broke during preparation of sawed sections.

"weak" mortars is undoubtedly an erroneous concept when considered in terms of performance in mortar-brick assemblages or in a wall or structure.

Summary

A program of testing has been developed which is based on the use of mortar-brick assemblages of sufficient size to afford convenient evaluation in the laboratory. Tests made on these specimens have indicated the following:

(1) The use of lime in mortar reduces the tendency for the mortar joint to leak.

(2) The high lime mortars substantially reduce the efflorescence of the mortar-brick assemblages.

(3) The presence of lime in the mortar increases the bond between brick and mortar and forms well integrated structural 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 contradistinction to this, the assemblages made with lime-free mortars tend to break at the interface between the mortar and brick; generally demonstrating a lower overall flexural strength.

(4) It is indicated that repetitive wetting and drying conditions are favorable to improving the watertightness of a high lime mortar-brick assemblage.

(5) The use of mortar-brick assemblages appears to provide information on strength and performance of masonry construction which may be more revealing than measurements made on the individual brick or mortar components.

It is realized that there are many more tests that should be run before all of the parameters under consideration can be accurately defined. It is felt, however, that the methods employed substantially demonstrate the performance of the materials that may be expected in the field and, at the same time, afford laboratory procedures which are both convenient and simple to set up. It is indicated that the inclusion of quantities of lime in mortar formulations is desirable. ☆