FACTORS AFFECTING THE STRENGTH OF MASONRY OF HOLLOW UNITS

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ABSTRACT

A study was made of the data reported in University of Illinois Bulletin No. 27 and Bureau of Standards Technologic Papers Nos. 238 and 311 in order to determine the importance of some of the factors affecting the strength of masonry of hollow units. For end-construction walls a simple empirical equation was found to express fairly well the relation between the strength of the walls and certain easily determined properties. For both end and side construction, the geometrical properties of the units appeared to have an important effect, and the strength of the units was not a close measure of the effect of their characteristics on the strength of the walls.

CONTENTS

I. INTRODUCTION

Allowable working stresses for walls of hollow units for buildings usually are the same for units having equal compressive strengths. These stresses are different with different mortars, but appear to be based upon the assumption that the compressive strength is the only property of the unit affecting the strength of walls. The strength values obtained in tests of large masonry specimens indicate strongly that there are other properties of the units which have an important effect on the strength of masonry, and it seemed worth while to study further the test data and to find, if possible, a better measure of masonry strength.

II. THE TEST DATA

The reports of Talbot and Abrams[1], Whittemore and Hathcock[2], and Stang, Parsons, and Foster[3] give the results of tests on large masonry specimens of hollow clay units in which the arrangement (bonding) of the units was similar to that used in ordinary building construction. Moreover, these reports contain rather complete data on physical tests of the materials and descriptions of the method of construction and the workmanship. A summary of the data pertaining to compressive tests under concentric loading of end-construction masonry (cells vertical) with broken joints is given in Table 1. A similar summary of the data pertaining to side-construction walls (cells horizontal) is given in Table 2.

[1] Tests of Brick Columns and Terra Cotta Block Columns, Univ. of Illinois Bul. No. 27; 1908.
[2] Some Compressive Tests of Hollow-Tile Walls, B. S. Tech. Paper No. 238, 1923.
[3] Compressive and Transverse Strength of Hollow Tile Walls, B. S. Tech. Paper No. 311; 1926.

TABLE 1.—*Compressive strength of end-construction masonry of hollow units*

Designation	Source of data	Author's specimen Nos.	Type of units and size (in inches)	Mortar mixture by volume [1]	Mortar		Estimated ratio of bearing area to gross area b	Compressive strength of units		Compressive strength of masonry (gross area) M
					Specimens	Compressive strength m		Gross area u	Net area	
						Lbs./in.^{2}		*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}
1	Bulletin 27	1, 2	3-cell 4 by 8.5 by 8 (thick shells).	1C:2S			0.85	3,470	4,100	2,880
2	do	3, 4	do	do			.85	3,470	4,100	3,070
3	do	5, 6	do	do			.74	3,470	4,100	2,950
4	do	8, 15	do	1C:3S	6-inch cubes	3,400	.74	5,170	6,110	4,300
5	do	12	do	do	do	3,130	.74	5,170	6,110	3,300
6	do	17	do	do	do	3,370	.74	5,170	6,110	3,050
7	do	18, 19	do	1C:5S			.74	5,170	6,110	3,350
8	Technologic Paper 238	1, 2, 3	XXX, 12 by 12 by 12	1C:1/4L:3S	2-inch cubes	2,150	.41	2,850	6,930	933
9	do	4, 5, 6	XXX, 6 by 12 by 12	do	do	2,150	.47	4,020	8,520	1,020
10	do	7, 8, 9	XXX, 8 by 12 by 12	do	do	2,150	.46	2,320	5,010	1,040
11	do	25, 26	XXX, 12 by 12 by 12	do	do	2,150	.45	1,680	3,770	930
12	do	27, 28	XXX, 6 by 12 by 12	do	do	2,150	.53	1,900	3,610	690
13	Technologic Paper 311	1-E-1	6-cell, 8 by 12 by 12	1-1/4L:3S	2 by 4-inch cylinders	85	.19	1,830	4,470	90
14	do	1-E-2	do	1C:1-1/4L:6S	do	760	.19	1,830	4,470	275
15	do	4-E-2	do	do	do	760	.23	1,270	2,740	295
16	do	6-E-2	XXX, 8 by 12 by 12	do	do	760	.34	2,100	4,260	370
17	do	2-E-2	6-cell, 12 by 12 by 12	do	do	760	.25	1,860	4,940	335
18	do	1-E-3	6-cell, 8 by 12 by 12	1C:1-1/4L:4S	do	1,190	.26	1,830	4,470	460
19	do	5-E-3	do	do	do	1,190	.28	2,840	6,470	550
20	do	6-E-3	XXX, 8 by 12 by 12	do	do	1,190	.49	2,100	4,260	650
21	do	7-E-3	do	do	do	1,190	.39	2,030	5,280	610
22	do	9-E-3	Double shell, 8 by 12 by 5	do	do	1,190	.30	3,320	6,900	555
23	do	1-E-4	6-cell, 8 by 12 by 12	1C:3S	do	1,990	.19	1,830	4,470	355

[1] C=cement, L=lime and S=sand.

TABLE 2.—*Compressive strength of side construction masonry of hollow units*

Designation	Source of data	Author's specimen Nos.	Type of unit and size (in inches)	Mortar: Mixture by volume [1]	Mortar: Specimens	Mortar: Compressive strength m	Compressive strength of units: Gross area u	Compressive strength of units: Net area	Compressive strength of masonry (gross area) M
						Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
24	Technologic Paper 238	10, 11, 12	XXX, 12 by 12 by 12	1C:1/4L:3S	2-inch cubes	2,150	840	3,780	375
25	do	13, 14, 15	XXX, 8 by 12 by 12	do	do	2,150	1,240	5,460	395
26	do	16, 17, 18	XXX, 6 by 12 by 12	do	do	2,150	1,665	5,930	700
27	do	29, 30	do	do	do	2,150	585	1,870	380
28	Technologic Paper 311	1-S-1	6-cell, 8 by 12 by 12	1-1/4L:3S	2 by 4 inch cylinders	85	500	2,210	165
29	do	1-S-2	do	1C:1-1/4L:6S	do	760	500	2,210	285
30	do	8-S-2	H-shaped, 8 by 10¼ by 12	do	do	760	1,040	3,350	455
31	do	2-S-2	6-cell, 12 by 12 by 12	do	do	760	580	2,620	385
32	do	1-S-3	6-cell, 8 by 12 by 12	1C:1-1/4L:4S	do	1,190	500	2,210	405
33	do	4-S-3	do	do	do	1,190	330	1,290	230
34	do	5-S-3	do	do	do	1,190	1,740	7,080	500
35	do	6-S-3	XXX, 8 by 12 by 12	do	do	1,190	430	1,500	240
36	do	10-S-3	2-cell, 8 by 5 by 12	do	do	1,190	820	3,740	335
37	do	13-S-3	3-cell, 8 by 5 by 12	do	do	1,190	900	3,540	440
38	do	14-S-3	T-shaped, 8 by 6¼ by 12	do	do	1,190	340	1,150	305
39	do	15-S-3	do	do	do	1,190	630	1,870	430
40	do	14-S-3	do	do	do	1,190	340	1,150	340
41	[2]	16-S-3	Cube, 8 by 8 by 8	do	do	1,190	780	3,060	430
42	Technologic Paper 311	1-S-4	6-cell, 8 by 12 by 12	1C:3S	do	1,990	500	2,210	360

[1] C=cement, L=lime and S=sand.

[2] Unpublished data.

No other data[4] on tests of large masonry specimens of either hollow clay or hollow concrete units with as complete information on materials and workmanship have come to my attention. Indeed, there appears to be no published information of this character on the strength of masonry of hollow concrete units.

Values of the strength of the mortar specimens are lacking in a few cases as indicated in Table 1. And the strength (2,150 lbs./in.^{2}) given for the 1C:1/4L:3S mortar at the age for testing the masonry was estimated from the values of strengths at the ages of 7 days and 6 months.

The ratios b in Table 1 of bearing area to gross area of masonry are estimates based upon the dimensions of the units and descriptions (and observations in the case of the tests reported in Bureau of Standards Technologic Paper No. 311) of the workmanship and method of laying the units.

III. STUDIES OF THE DATA

1. GENERAL

It is expected that the compressive strength M of a masonry specimen would depend chiefly on the compressive strength of the units u, the compressive strength of the mortar m, other strength properties and the elastic properties of the materials of the units and of the mortar and on the various dimensions describing the shapes and sizes of the masonry and its component parts. If these quantities are the only ones having a significant influence, the relations between them may be expressed according to the principle of dimensional homogeneity[5] by the following equation:

$$M=KuF\left(\frac{m}{u}, R_1, R_2 \ldots R_m, r_1, r_2 \ldots r_n\right) \tag{1}$$

K = an unknown numerical constant.

F = an unknown function of the dimensionless ratios within the brackets.

$R_1, R_2 \ldots R_m$ = ratios of other strength properties and of the moduli of elasticity of the materials to u.

$r_1, r_2 \ldots r_n$ = ratios of other linear dimensions of the masonry to a chosen linear dimension L, or ratios of areas to a chosen area. In any case, geometrical ratios describing the shape and size of the masonry and its component parts.

It is, of course, optional which of the strength properties or elastic moduli of the materials is chosen in the place of u, provided the R's contain all of the quantities of the same dimensions that have an influence on M. The form of the function F and the value of the constant K can be determined only from test data.

The obvious direct way to determine the form of the function F by a set of new experiments would be to vary the dimensionless ratios

[4] Data on the strength of walls 3 feet long and 3 feet high are reported by Ingberg and Foster in the paper "Fire Resistance of Hollow Load-Bearing Wall Tile," B. S. Jour. Research, 2 (RP37); 1928.

[5] Also known as the principle of similitude or when applied to mechanical problems as the law or principle of dynamic similarity. Those not already familiar with the subject will enjoy reading Dr. Edgar Buckingham's excellent presentation in the paper "Model Experiments and the Forms of Empirical Equations." Trans. Am. Soc. Mech. Engrs., 37, p. 263; 1915.

of F, one at a time, holding all the others constant. Then writing the equation (1) in the form

$$\frac{M}{u}=KF\left(\frac{m}{u}, R_1, R_2\text{--}R_m, r_1, r_2\text{--}r_n\right) \tag{1a}$$

the relation between $\frac{M}{u}$ and each of the ratios could be determined. When using the common materials for hollow walls, however, it is sometimes impracticable to vary one ratio over a wide range without affecting the values of some of the others. For example, mortars having a wide range in compressive strengths also will vary in other strength properties and in elastic properties. The present purpose, however, is to find what useful information may be derived from existing data.

It is apparent from the outset that, with so few data and so many variable factors, the form of the presumably complete equation (1) or (1a) can not be determined at present. In order to obtain useful results it becomes necessary to simplify the expression by omitting some of the ratios. In doing this it is necessary to omit none that has a large influence if the resulting equation is to be a fair approximation, and, if the results are to be useful, to include only those terms based on values that may be readily determined in practice.

2. END-CONSTRUCTION MASONRY

The test results do not provide sufficient data of the right sort to determine the manner in which the ratios (r_1, r_2--r_n) describing the sizes and shapes of the masonry, masonry units, and mortar joints enter into the equation. If as a first approximation one ratio were to be selected, which by itself would serve to indicate roughly the effects of all of the geometrical ratios, it seems likely that the one best suited would be the ratio b of the bearing area to the gross area of the masonry. Numerically the value of b is equal to the ratio of the total area, at the plane of a joint, of the material of the units given a bearing by the mortar, to the gross area of the masonry at the same plane. If as a further approximation all the R's are omitted, equation (1) may be written

$$M=kuf\left(\frac{m}{u}, b\right)$$

or

$$\frac{M}{u}=kf\left(\frac{m}{u}, b\right) \tag{2}$$

where f is some unknown function of the ratios within the brackets and k is an unknown numerical constant.

By comparing the distributions of the values in Figures 1 and 2,[6] it appears that the value of b has an important effect on the strength

[6] The proportions for and the properties of the 1C:3S and the 1C:1/4L:3S mortars were so near alike that one symbol was used in the figures to represent values relating to both.

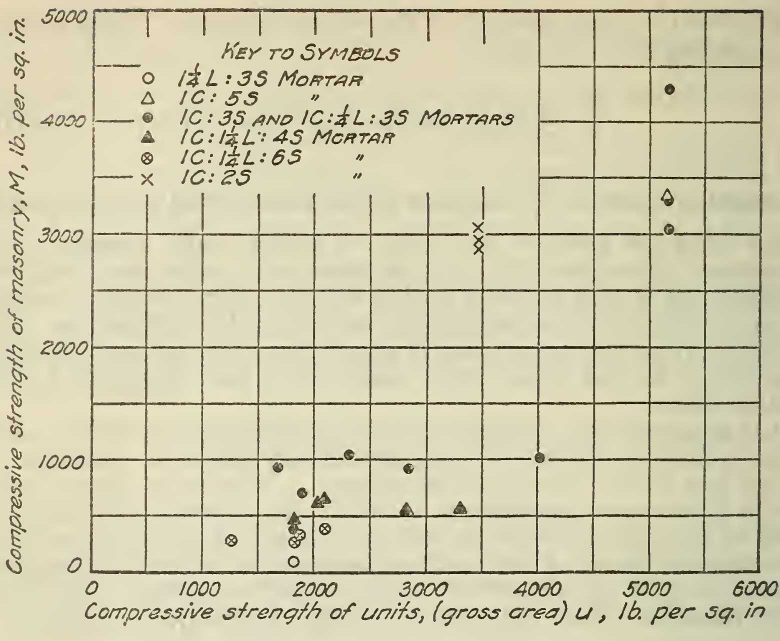

FIGURE 1.—*Relation between compressive strength (gross area) of end-construction masonry and compressive strength of units*

The proportions for the mortars are by volumes, with the abbreviations C for cement, L for lime, and S for sand.

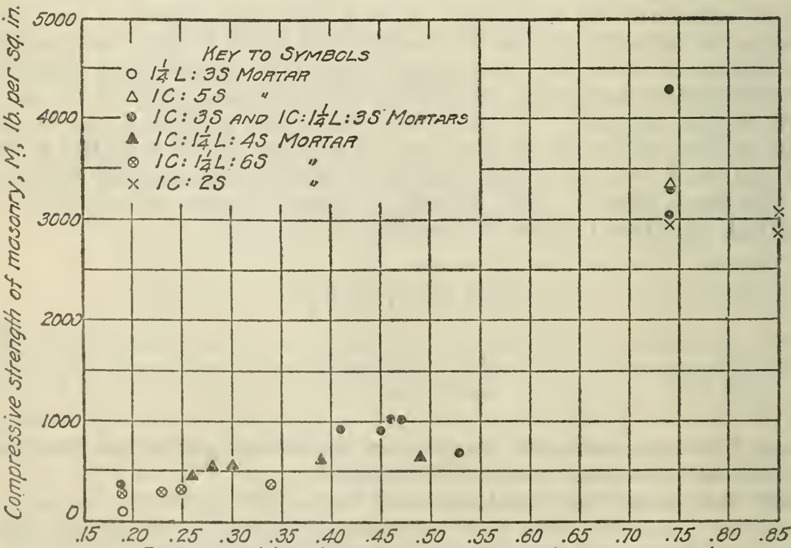

FIGURE 2.—*Relation between compressive strength (gross area) of end-construction masonry and the ratio of net bearing area in masonry to gross area*

The proportions for the mortars are by volumes, with the abbreviations C for cement, L for lime, and S for sand.

of the masonry M. Since the data are inadequate for determining the relation between $\frac{M}{u}$ and b while $\frac{m}{u}$ remains constant, all of the values are plotted in Figure 3. By considering, one at a time, the values for which $\frac{m}{u}$ varied only over a small range there seemed to be a rough relation between $\frac{M}{u}$ and b. Such meager data do not justify any refinements in the selection of a cumbersome form for representing the relationship. A linear relation probably is close enough for the purpose and on that basis the approximation becomes

$$\frac{M}{bu}=K_1 f\left(\frac{m}{u}\right) \tag{3}$$

where f is an unknown function of $\frac{m}{u}$ and K_1 is an undetermined numerical constant.

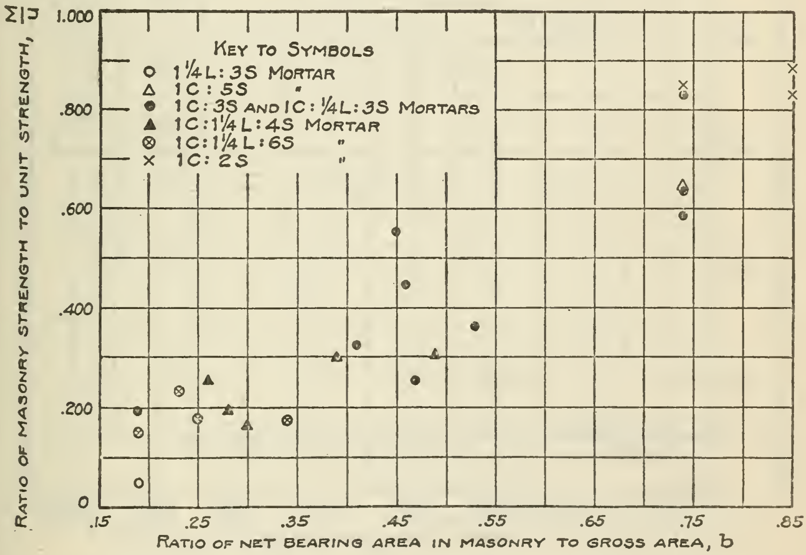

FIGURE 3.—*Relation between $\frac{M}{u}$ and b, where*

M=compressive strength of masonry (gross area) lbs./in.^{2}
u=compressive strength of units (gross area) lbs./in.^{2}
b=ratio of bearing area in masonry to gross area

The proportions for the mortars are by volume, with the abbreviations C for cement, L for lime, and S for sand.

Without burdening the reader further with the details of developing the approximate equation, it was found that the following relation fits the data for end construction masonry as well as any other equally simple form investigated:[7]

$$\frac{M}{bu}=K_1\left(\frac{m}{u}\right)^{1/2} \tag{4}$$

or

$$M=K_1 b\sqrt{mu}$$

[7] Other forms of equations were investigated, but the main point to be emphasized is the necessity for considering other factors than u and m, and this is done equally well by the more simple form (4).

The value of K_1 is approximately unity. A comparison between values of masonry strength calculated by means of equation (4) with test results is shown in Figure 4. Different empirical equations for expressing the relations between the quantities of equation (2) may be found readily, but with so many factors (quantities) left out of consideration it is useless to begin splitting hairs here.

The scattering of the plotted points of Figure 4 gives an indication of the incompleteness of equation (4). A part of the scattering may be attributed rather definitely to known causes. For example, the two values for which the ratio of test to estimated strength are lowest pertain to specimens 12 feet high and only 6 inches thick. It seems likely that the large ratio of height to thickness of the walls accounts in part for the unusually low strengths of these specimens. Of the

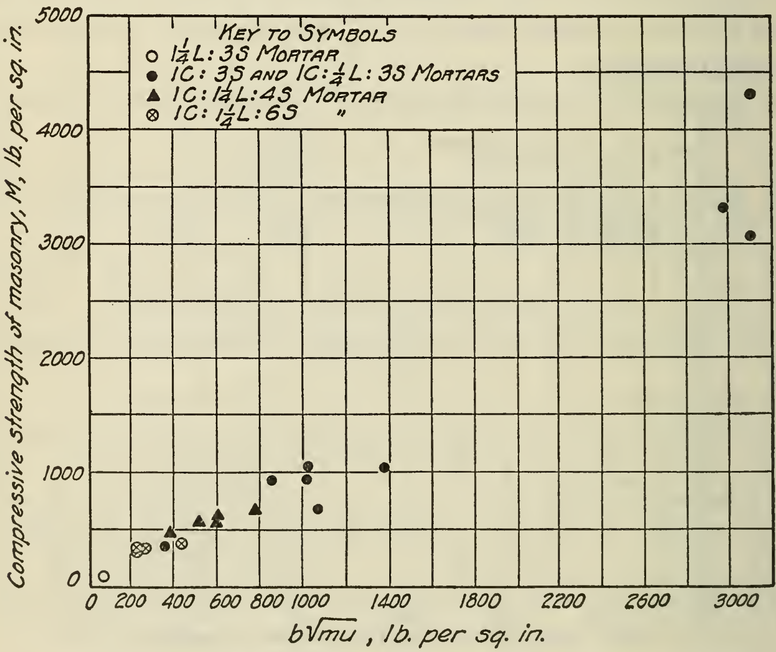

FIGURE 4.—*Relation between compressive strength (gross area) of end-construction masonry and $b\sqrt{mu}$, where*
b = ratio of bearing area in masonry to gross area
m = compressive strength of mortar specimens, lbs./in.²
u = compressive strength (gross area) of units, lbs./in.²

three values from the data of Talbot and Abrams, one pertains to masonry specimens built with units specially selected because of their uniformity of size and shape, another to units having warped bearing surfaces and the third to a "poorly laid" masonry specimen. Obviously, such factors as these are not taken into account by equation (4).

Among the several other possible causes of the scattering, one difficult to evaluate is that the properties of the mortar in the joints probably are different than those of the mortar specimens. Water absorbed from the mortar by the units and differences in curing conditions would be likely to affect the relations between the properties of the joints and specimen mortars. Another possible cause for deviations is the fact that the size and shape of the mortar specimens were not the same in the three investigations. Such variables also suggest reasons why it would be quite useless to attempt a great refinement in selecting a form of equation to represent the available data.

3. SIDE-CONSTRUCTION MASONRY

The relation between the comprehensive strengths (gross area) of side-construction masonry and of the units is shown in Figure 5. Here the relation seems to be somewhat more regular than that for end construction masonry illustrated in Figure 1.

A part of the lack of regularity in the distribution of the plotted points in Figure 5 is assignable to known causes. The masonry specimens designated Nos. 33 and 35 in Table 2 were built with units

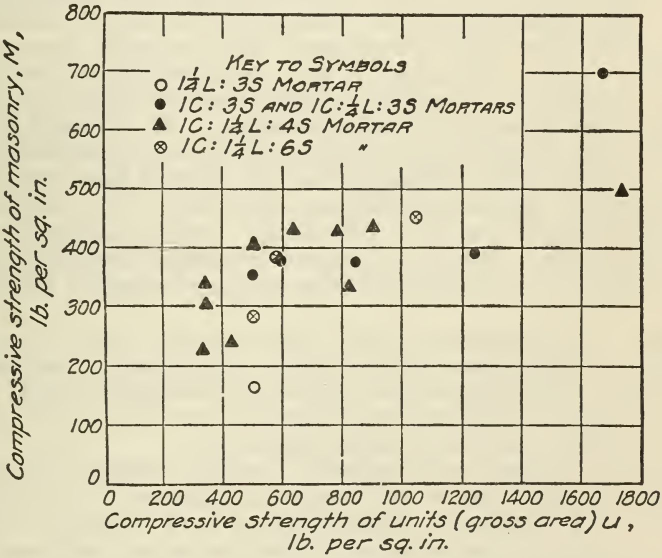

FIGURE 5.—*Relation between comprehensive strength (gross area) of side-construction masonry and compressive strength of units*

The proportions for the mortars are by volume with the abbreviations C for cement, L for lime, and S for sand.

having irregular bearing surfaces. A portion of the bearing shells near the vertical mid plane of the walls was concave toward the mortar joint. It is understood that these tiles were formed in this manner purposely in order to lessen the likelihood of there being a continuous mortar joint through walls. The recesses in the bearing shells resulted in there being a continuous bearing only for the outer shells; for ordinary tile of this design about 70 per cent of the net sectional area would be given a direct bearing.

Differences in the ratios between the thickness of the bearing (horizontal) shells and the horizontal distances between the supports provided by the vertical shells and webs probably is another major cause for the lack of a closer relationship between the variables shown in Figure 5. Comparing No. 36 with No. 37 in Table 2, it is seen that the masonry with 3-cell tiles was stronger than that with the 2-cell units. In fact, all of those having relatively closely spaced vertical shells and webs (Nos. 30, 37, 38, 39, and 40) lie above an average line through the points of Figure 5. It has been observed [8] that in many cases the cracking of the horizontal shell in contact with the mortar was the first sign of the failure of side-construction walls in compressive tests. It seems apparent, therefore, that the bending strength of the shells is important with some unit designs.

However, the available data relating to side construction masonry are inadequate for a determination of the form of equation (1). In fact the two important factors mentioned in the preceding paragraphs can not be well evaluated at present.

For the end-construction walls account was taken of the workmanship by the ratio b, this ratio being a function of the design of the units and the proportion of the shells and webs given mortar bearing by the mason. No such simple way of evaluating the effect of workmanship in side-construction walls is apparent. It is probable, however, that there were marked differences in the workmanship of the different masons. Walls Nos. 32 and 42 of Table 2 were of identical construction except for the mortar and workmanship. The strength ($M=405$ lbs./in.^{2}) of No. 32 with 1C:1–1/4L:4S mortar was appreciably greater than the strength ($M=360$ lbs./in.^{2}) of No. 42 with the much stronger 1C:3S mortar. The tests of Ingberg and Foster [9] gave, on the average, higher strengths for walls with cement mortar than for those with 1C:1L:4S mortar. Hence, it is logical to assume that with the same workmanship No. 42 would have been stronger instead of weaker than No. 32.

Without having some way for evaluating the effects of workmanship, direct comparisons to determine the relations between wall strength and properties of the mortars are not easily made. About the only general statement warranted is that the use of stronger mortars usually results in stronger masonry.

In so far as the units are concerned, the data indicate that the three following properties have an important effect on the strength of masonry: (1) Compressive strength, (2) ratio of thickness of bearing shells to maximum span between vertical supports (shells and webs), and (3) features of design affecting the proportion of area given a bearing at bed joints.

IV. CONCLUDING REMARKS

Equation (4) must be considered as only a rough approximation. It is obvious that no such simple expression could be correct since it does not take account of many factors, such as the elastic properties of the materials and the size and shape of the masonry and its parts. In addition to the cause mentioned previously, the methods of testing masonry, the units and the mortar would affect the values derived from the tests and, hence, the agreement between any predicted and determined values.

In addition to the general size and shape of the masonry and the units, two other geometrical properties, namely, the thickness of the

[8] B. S. Tech. Paper No. 311, p. 339.

[9] See Table 2, B. S. Research Paper No. 37.

mortar joints and the regularity of the bearing surfaces of the units are of importance. A discussion of the effect of the latter is given by Talbot and Abrams, but the effect of neither of them has been considered here.

Nevertheless the test data indicate that properties of the units other than the compressive strength must be considered for even rough estimates of the compressive strength of masonry. The values shown in Figures 2, 3, and 4 indicate that the ratio *b* of the net bearing area to the gross sectional area of the masonry is an important property with end-construction masonry. For side-construction masonry it appears that the two factors (1) the ratio of thickness of bearing shells to maximum span between supports and (2) the proportion of area given a bearing, should be considered.

WASHINGTON, February 24, 1931.