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COMPRESSIVE AND TRANSVERSE STRENGTH OF HOLLOW-TILE WALLS

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By A. H. Stang, D. E. Parsons, and H. D. Foster

ABSTRACT

Strength tests of 70 hollow-tile walls constructed with ordinary workmanship and built under average indoor conditions were made. The walls tested were all 6 feet long and 9 feet high and either 8 or 12 inches thick. Fourteen different lots of tile and four different mortar mixtures were used in their construction. Twenty-seven of the walls were subjected to a transverse test before being tested in compression under central loading. Fifty-three of the walls were tested in compression under central loading and 17 under eccentric loading.

The mortar and workmanship seemed to be the most important factors affecting the strength of the end construction walls. Those with cement-lime mortar (IC:11/4L:4S) were about 5.1 times the strength of those with lime mortar (11/4L:3S). The mortar had relatively less effect upon the strength of the side construction walls. Those with cement-lime mortar had 2.4 times the strength of those with lime mortar. There seemed to be no constant ratio between the strength of the walls and the strength of the tiles, but, in general, using the same mortar, this ratio decreased with an increase in tile strength. With the eccentrically loaded walls, the maximum loads supported were about 60 per cent of the loads for similar walls centrally loaded.

The transverse strength of the walls was largely affected by differences in mortar and in the position of the tiles. In general, the stronger mortars gave higher transverse strengths, and the wall having the tiles laid on the side were stronger under side load than with the tiles on end.

CONTENTS

	Page
I. Introduction	318
II. Description of the specimens and of the test methods	319
1. Tiles	319
2. Mortar	321
3. Walls	322
(*a*) Types and notation	322
(*b*) Size	329
(*c*) Workmanship and building conditions	329
(*d*) Construction data	330
(1) Rate of building	330
(2) Mortar materials	332
(*e*) Aging conditions	332
(*f*) Age	332
(*g*) Method of testing	332
(1) Transverse tests	332
(2) Compressive tests, central loading	333
(3) Compressive tests, eccentric loading	334

Page
III. Results of the tests with discussion 336
1. Basis of computations 336
2. Tiles 336
3. Mortar 337
4. Transverse tests of the walls 337
5. Compressive tests of the walls with central loading 338
(a) Deformation of the walls 338
(b) Behavior of walls under load 339
(c) Compressive strength of centrally loaded walls 341
(1) Effect of mortar 341
(2) Effect of wall construction, end, side, and mixed 345
(3) Effect of strength of single tiles 347
(4) Effect of thickness of walls and design of tiles 348
(d) Relation between strength and modulus of elasticity of walls 349
6. Compressive tests of the walls with eccentric loading 349
(a) Deformations in walls 349
(1) Modulus of elasticity of walls 349
(2) Variation of deformations in walls with height 350
(3) Apparent eccentricity from compressometer data 350
(b) Compressive strength of eccentrically loaded walls 351
IV. Conclusions 352

I. INTRODUCTION

The widely varied requirements for hollow-tile walls in existing codes and specifications have emphasized the need for further information regarding their strength. The safe and economical design of hollow-tile walls, like other masonry structures, requires not only a knowledge of the properties of the materials which make up the composite masonry members, but also the strength of the walls or other members as a whole. In contrast with some other materials of construction, the laws deduced from laboratory tests of small specimens of the materials used in masonry construction are not readily applicable to structural design. The difficulty of applying the knowledge gained from laboratory tests is further increased by the variations which may exist between the conditions of construction in the laboratory and in the field. Consequently, until the factors which govern the strength of masonry walls are better understood, the results of tests on specimens which are comparable in size and workmanship to commercial masonry are of the greatest value.

In recognition of the need for further information regarding the strength of different types of masonry, strength tests have been made at the Bureau of Standards from time to time for a number of years. A report[1] has been published on the compressive tests of some

[1] B. S. Tech. Paper No. 238, Some Compressive Tests of Hollow Tile Walls, Whittemore and Hathcock.

hollow-tile walls built with much better workmanship than is obtained in practice.

The present paper describes the strength tests of 70 hollow-tile walls which were recently made at the Bureau of Standards. Walls built of different designs of tiles and with different mortars were subjected to transverse tests, compressive tests with central loading, and compressive tests with eccentric loading. It is believed that the results are of general interest because they were obtained with specimens which were comparable in size and workmanship to commercial hollow-tile walls.

Members of the Hollow Building Tile Association (J. T. Howington, president), Chicago, Ill., gave the tiles and the association paid for building the walls. The Hydraulic Pressed Brick Co., Washington, D. C., donated the brick. F. J. Huse, chief engineer of the association, assisted in planning the investigation.

The bureau staff supervised the construction of the walls, made the tests, and prepared this report. Acknowledgments are especially due to C. T. Ervin and G. Murphy, laboratory assistants, for aid in the inspecting and testing the specimens and computing the data.

II. DESCRIPTION OF THE SPECIMENS AND OF THE TEST METHODS

1. TILES

The hollow tiles came from Ohio, New Jersey, Georgia, and Kentucky and were made from surface clay, fire clay, or shale.

The following designs of tiles were used, all of which are shown in Figure 1:

1-cell, 3¾ by 5 by 12 inches (*11*, fig. 1).

2-cell, 8 by 5 by 12 inches (*10*, fig. 1).

3-cell, 8 by 5 by 12 inches (*13*, fig. 1).

3-cell, 3¾ by 12 by 12 inches (*3*, fig. 1).

6-cell, 8 by 12 by 12 inches (all cells equal) (*1*, *4*, and *5*, fig. 1).

6-cell, 8 by 12 by 12 inches (XXX, cells not all equal) (*6* and *7*, fig. 1).

6-cell, 12 by 12 by 12 inches (*2*, fig. 1).

T-shaped, 8 by 6¼ by 12 inches (*14* and *15*, fig. 1).

H-shaped, 8 by 10¼ by 12 inches (*8*, fig. 1).

Double shell, 8 by 12 by 5 inches (*9*, fig. 1).

Brick (*12*, fig. 1) were used in two of the walls.

The kind of clay from which the tiles were made, their source, nominal size, and design are given in Table 1.

TABLE 1.—*Physical properties of hollow tiles and brick*

Tile lot number	Kind of clay	Source	Design of tiles	Nominal size in inches	Number of specimens	Position in which tested	Average area under compression		Average weight	Average modulus of elasticity (net area)	Compressive strength				Absorption	
											Range	Average	Range	Average	Range	Average
							Gross	Net			Gross area		Net area			
							Sq.in.	*Sq.in.*	*Lbs.*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*
1	Fire clay, dense burning.	Ohio	6-cell	8 by 12 by 12	5	End	98.3	40.1	35.2	2,875,000	1,060–2,510	1,830	2,560–6,040	4,470	8.9–13.4	11.5
1	do	do	do	do	4	Side	97.4	22.1		1,588,000	440– 540	500	1,990–2,390	2,210	12.8–13.7	13.2
2	do	do	do	12 by 12 by 12	5	End	152.3	57.4	50.0	4,921,000	1,220–2,420	1,860	3,210–6,290	4,940	8.4–12.2	9.8
2	do	do	do	do	5	Side	146.0	32.6		2,019,000	350– 750	580	1,540–3,470	2,620	7.8–10.8	9.5
3	do	do	3-cell	3¾ by 12 by 12	5	End	48.9	22.9	19.4		1,370–2,100	1,740	2,960–4,520	3,720	9.3–13.0	11.2
4	Fire clay, open burning.	New Jersey	6-cell	8 by 12 by 12	5	do	99.5	46.3	36.2	2,145,000	1,020–1,500	1,270	2,140–3,170	2,740	15.1–18.3	16.9
4	do	do	do	do	5	Side	95.5	24.7		2,041,000	280– 420	330	1,070–1,640	1,290	15.8–19.8	17.0
5	Shale	Kentucky	do	do	5	End	94.1	41.4	38.6	5,750,000	2,530–3,610	2,840	5,840–8,260	6,470	5.6– 7.8	6.7
5	do	do	do	do	5	Side	91.8	22.6		4,327,000	1,370–2,110	1,740	5,480–8,510	7,080	4.6–10.4	6.4
6	Surface clay	New Jersey	XXX	do	5	End	90.6	44.6	35.8	4,538,000	1,610–2,790	2,100	3,370–5,680	4,260	9.2–13.0	11.5
6	do	do	do	do	5	Side	91.2	26.3			300– 580	430	980–2,120	1,500	8.5–11.3	9.9
7	Fire clay, dense burning.	Ohio	do	do	5	End	91.7	35.5	30.5	3,915,000	1,140–2,660	2,030	2,840–6,960	5,280	5.8–12.6	8.5
8	do	do	H-shaped	8 by 10¼ by 12	5	Side	99.5	30.8	34.9	2,207,000	730–1,390	1,040	2,350–4,550	3,350	10.1–14.3	12.6
9	do	do	Double shell	8 by 12 by 5	5	End	94.5	45.4	17.1		3,200–3,560	3,320	6,680–7,300	6,900	5.2– 7.4	6.2
10	do	do	2-cell	8 by 5 by 12	5	Side	92.9	20.2	14.4		560– 980	820	2,580–4,530	3,740	6.5– 7.4	6.8
11	do	do	1-cell	3¾ by 5 by 12	5	do	46.3	14.8	9.0		1,030–1,330	1,190	3,190–4,370	3,720	5.4–10.0	8.1
12	Hydraulic pressed brick.[1]	Virginia		2¼ by 3¾ by 8	10	Flat	30.5	30.5			4,330–6,860	5,690	4,330–6,860	5,690	12.3–15.0	13.6
13	Fire clay, dense burning.	Ohio	3-cell	8 by 5 by 12	5	Side	94.4	24.0	14.4		690–1,020	900	2,710–4,040	3,540	6.7– 9.8	7.4
14	Surface clay	Georgia	T-shaped	8 by 6¼ by 12	5	do	93.3	28.0	15.8		290– 400	340	930–1,310	1,150	13.2–15.0	14.4
15	do	New Jersey	do	do	8	do	96.3	32.2	18.0		520– 750	630	1,590–2,270	1,870	6.0–10.2	8.8

[1] Modulus of rupture of bricks ranged from 570 to 680 lbs./in.² with average 620 lbs./in.²

An examination showed that the tiles made from the shale and the dense-burning fire clay were practically free from laminations; that the tiles made from the open-burning fire clays contained some laminations; and that the tiles made from the surface clays contained many laminations.

Five tiles of each lot (except as noted in Table 1) were measured to determine their actual dimensions and were then tested for weight, compressive strength, and absorption in accordance with the methods of Tentative Specification C 34–24T of the American Society for Testing Materials.[2] In making the compressive tests the tiles were tested on end or on side, according to the position in which they were laid in the wall. The modulus of elasticity of the tiles, which were 10 inches or more in height, was determined from deformations under load measured over an 8-inch gauge length with a clamp type of compressometer having a single micrometer dial reading to 0.0001 inch.

2. MORTAR

The mortar mixes represent certain commonly used volume proportions. Measurement by volume, however, would have resulted in wider variations in the mortar compositions than seemed desirable, so that equivalent proportions by weight were used, assuming that 1 cubic foot of lime weighs 40 pounds and 1 cubic foot of cement weighs 94 pounds. The weight of the dry materials in a cubic foot of damp sand was determined by preliminary tests to be about 73 pounds. Since the weight of a cubic foot of damp sand, loose measure, varied with the moisture content, the moisture content of a sample of sand was determined each day during the construction of the walls and the weight necessary to make the desired amount of dry sand was computed. This value was used in proportioning the mortar for the day. Water was added to give the consistency desired by the mason and the amount of water recorded. All the mortar used was proportioned by these equivalent weights. The mortars will, however, for convenience be referred to by their volume ratios.

The four mortar mixtures were as follows:

Mortar No. 1.—Lime mortar (1¼L:3S) by volume 1¼ parts of lime to 3 parts of damp sand, loose measure· weight equivalents. 50 pounds of hydrated lime to 220 pounds of dry sand.

Mortar No. 2.—Cement-lime mortar (1C:1¼L:6S) by volume 1 part of cement to 1¼ parts of lime to 6 parts of damp sand, loose measure; weight equivalents, 94 pounds of Portland cement to 50 pounds of hydrated lime to 440 pounds of dry sand.

Mortar No. 3.—Cement-lime mortar (1C:1¼L:4S) by volume 1 part of cement to 1¼ parts of lime to 4 parts of damp sand, loose measure; weight equivalents, 94 pounds of Portland cement to 50 pounds of hydrated lime to 293 pounds of dry sand.

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[2] Proc. A. S. T. M., pt. 1, **24**, p. 818, 1924.

Mortar No. 4.—Cement mortar (1C:3S) by volume 1 part of cement to 3 parts of damp sand, loose measure; weight equivalents, 94 pounds of Portland cement to 220 pounds of dry sand.

Three cylinders (2 inches in diameter, 4 inches long) for compressive tests and three briquets (1 square inch in minimum section) for tensile tests were made from the mortar of each wall. After they had been taken from the molds they were placed on the walls they represented, as shown in Figure 5, and allowed to age under the same conditions. They were tested at the same age as the corresponding wall.

3. WALLS

(*a*) Types and Notation.—Seventy tile walls were built and tested. The types of construction used are shown in Figures 2, 3, and 4. Since 14 kinds of tiles, 3 methods of construction, and 4 mortars were used, it was necessary to adopt a notation so that the separate walls may be distinguished easily and designated conveniently. The designation was, therefore, first, a number to designate the tiles used in the wall to correspond to the tile lot numbers (lot No. 12 was brick) of Figure 1 and Table 1; second, a letter to denote the construction (E for end construction [figs. 2, 3, 10, and 12], S for side construction [figs. 2, 3, 4, and 9], and M for the mixed construction [fig. 6]); third, a number to designate the mortar mixture used, as explained above; and in some cases, fourth, a letter A or B, to distinguish the two similar wall specimens built of tiles of the same lot, with the same construction and mortar, and tested in the same manner. Thus 1–E–2 designates the walls built of tiles of lot No. 1 (fig. 1), with end construction (fig. 2–A), and with the No. 2 mortar (1C:1¼L:6S); 1–E–2–A refers to one of these walls. In those walls in which tiles of more than one type were used all the tile lot numbers are given in parentheses. Thus (1+3)–E–2 (fig. 2–C) were end construction walls, the tiles in which were alternately of lot No. 1 and lot No. 3; (10+11+12)–S–3 (fig. 4–C) were walls having a brick facing (lot No. 12) backed up with side construction tiles of lots Nos. 10 and 11.

No distinction is made in this report between side construction walls built of tiles designed, primarily, for side construction and side construction walls built of tiles designed, primarily, for end construction. In all cases where the axes of the cells of the tiles were horizontal the walls are referred to as side construction.

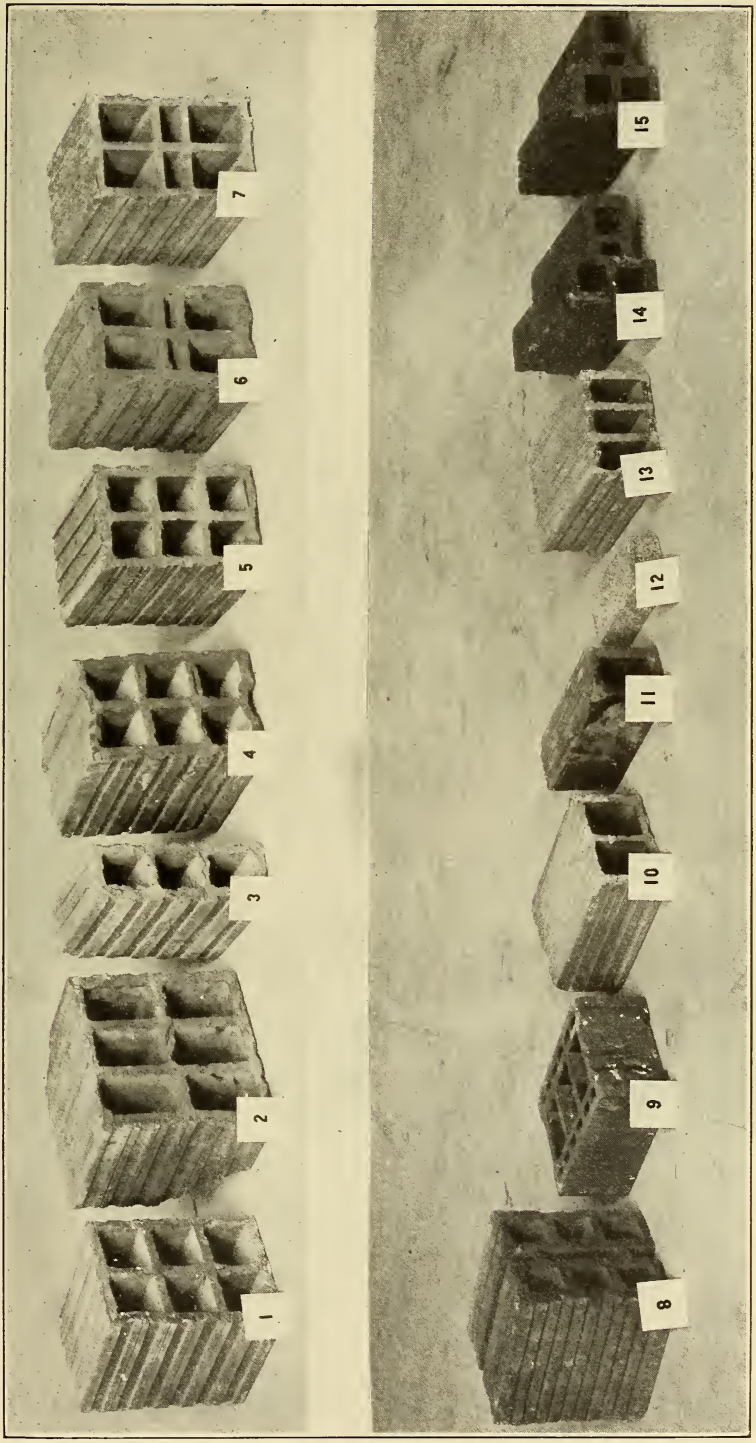

FIG. 1.—*The hollow tiles*

See Table 1 for description of the separate tiles

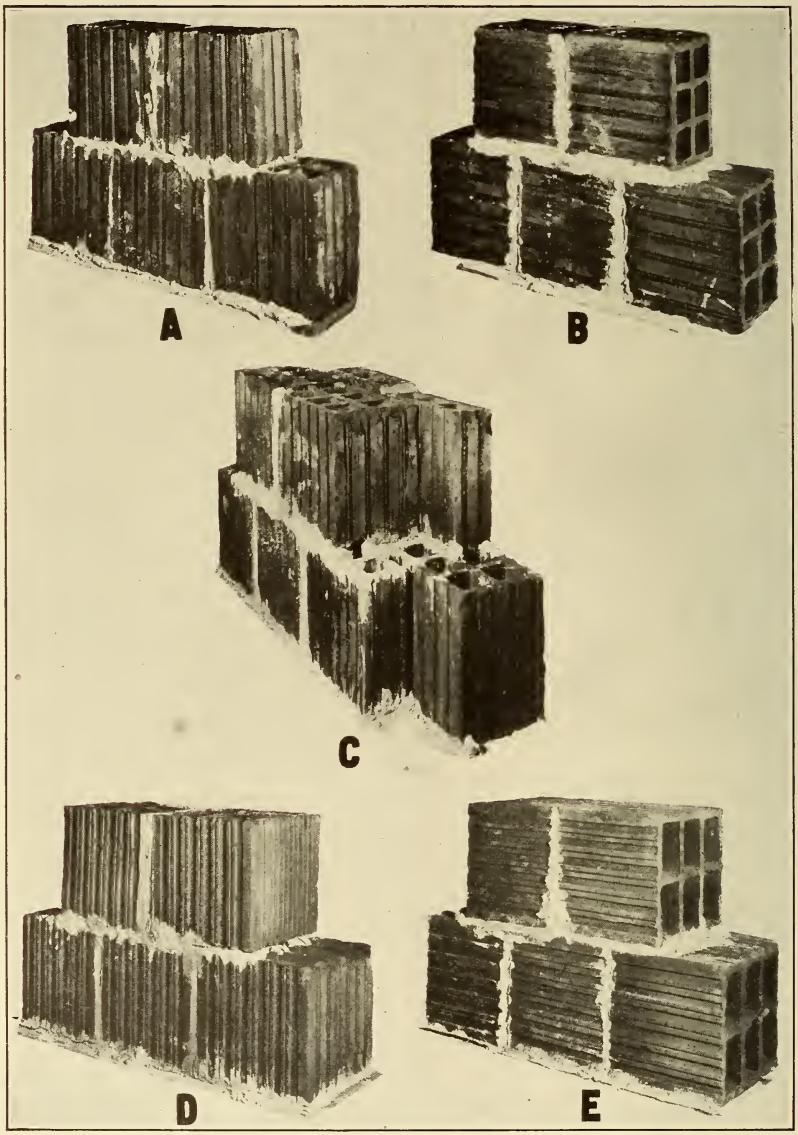

FIG. 2.—*Types of wall construction*

A, 8-inch end construction wall of 8 by 12 by 12 inch 6-cell tiles; *B*, 8-inch side construction wall of 8 by 12 by 12 inch 6-cell tiles; *C*, 12-inch end construction wall of 8 by 12 by 12 inch 6-cell tiles and of 3¾ by 12 by 12 inch 3-cell tiles; *D*, 12-inch end construction wall of 12 by 12 by 12 inch 6-cell tiles; *E*, 12-inch side construction wall of 12 by 12 by 12 inch 6-cell tiles

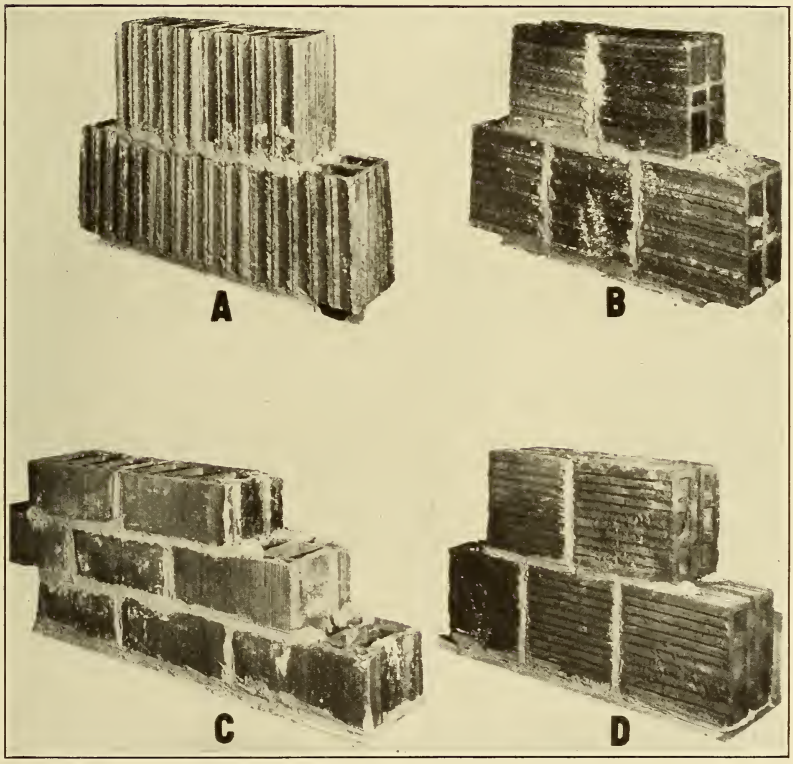

FIG. 3.—*Types of wall construction*

A, 8-inch end construction wall of 8 by 12 by 12 inch "XXX" tiles; *B*, 8-inch side construction wall of 8 by 12 by 12 inch "XXX" tiles; *C*, 8-inch end construction wall of 8 by 12 by 5 inch double shell tiles; *D*, 8-inch side construction wall of 8 by 10¼ by 12 inch "H"-shaped tiles

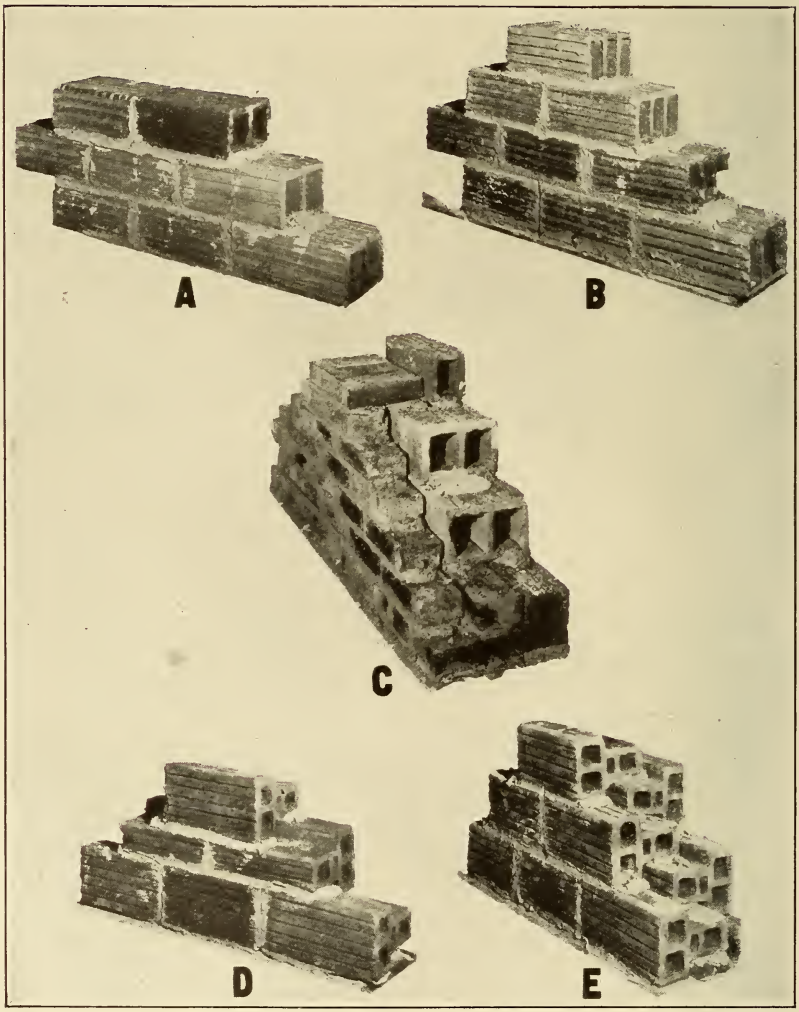

FIG. 4.—*Types of wall construction*

A, 8-inch side construction wall of 8 by 5 by 12 inch 2-cell tiles; *B*, 8-inch side construction wall of 8 by 5 by 12 inch 3-cell tiles; *C*, 12-inch wall of 8 by 5 by 12 inch 2-cell tiles, faced with brick (3¾ by 5 by 12 inch 1-cell tiles used as fillers); *D*, 8-inch side construction wall of 8 by 6¼ by 12 inch "T"-shaped tiles; *E*, 12-inch side construction wall of 8 by 6¼ by 12 inch "T"-shaped tiles

FIG. 5.—*Tile walls stored in the laboratory*

Note the mortar specimens on the walls

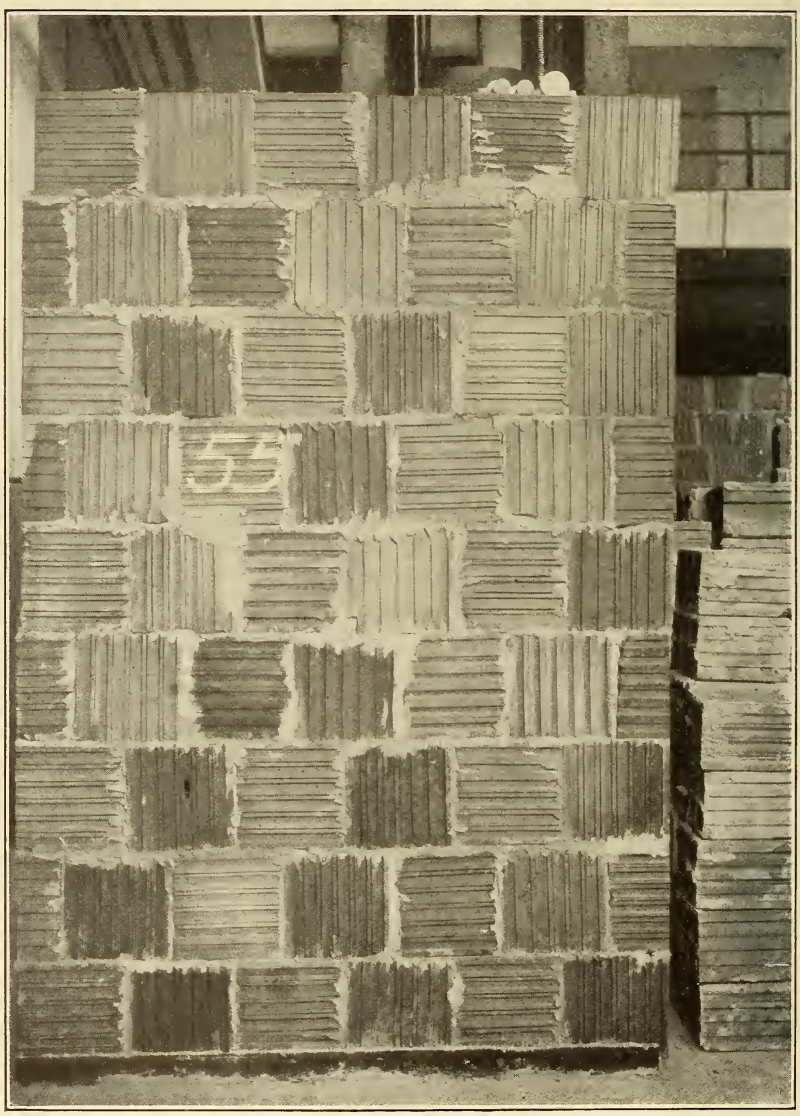

Fig. 6.—*Tile wall of mixed construction*

Wall 1-M-2-A before test

TABLE 2.—*Construction data of hollow-tile walls*

Designation of walls[1]	Wall thickness in inches	Number of walls	Number of tile courses	Rate of building walls in square feet per hour	Mortar materials used: Cement	Lime	Sand (dry)	Water
					Pounds per square foot of wall surface			
1-E-1	8	2	9	42	0.0	1.1	4.6	1.6
1-S-1	8	2	9	39	.0	.5	2.3	.8
1-E-2	8	4	9	53	.8	.4	3.5	1.1
1-S-2	8	4	9	46	.7	.4	3.3	1.0
1-E-3	8	4	9	36	1.6	.8	4.9	1.9
1-S-3	8	2	9	46	1.3	.7	4.1	1.6
1-E-4	8	2	9	40	1.6	.0	3.7	1.2
1-S-4	8	2	9	58	1.5	.0	3.5	1.0
1-M-2	8	2	9	62	.7	.4	3.5	1.2
4-E-2	8	2	9	51	1.0	.5	4.5	1.5
4-S-3	8	2	9	31	1.6	.8	5.0	1.7
5-E-3	8	2	9	26	1.4	.7	4.3	1.7
5-S-3	8	2	9	30	1.3	.7	4.2	1.6
6-E-2	8	1	9	66	.8	.4	3.5	1.2
6-E-3	8	1	9	30	1.7	.9	5.3	1.7
6-S-3	8	2	9	32	1.5	.8	4.6	1.6
7-E-3	8	2	9	33	1.6	.8	4.9	1.8
8-S-2	8	4	9	55	.7	.4	3.1	1.0
9-E-3	8	2	22	24	1.6	.9	5.0	1.9
10-S-3	8	4	21	23	1.5	.8	4.7	1.6
13-S-3	8	4	21	23	1.8	.9	5.5	1.9
14-S-3	8	2	22	22	2.2	1.2	6.8	2.4
15-S-3	8	2	22	19	2.3	1.2	7.0	2.7
2-E-2	12	4	9	32	1.0	.6	4.8	1.5
2-S-2	12	4	9	41	.8	.4	3.8	1.2
(1+3)-E-2	12	2	9	21	1.8	.9	8.2	2.4
(10+11+12)-S-3	12	2	21	9	4.9	2.6	15.2	5.1
14-S-3	12	2	22	16	3.8	2.0	11.9	4.4

[1] The symbols listed below in this column represent, in the order used: Tile lot number, construction, and mortar number.

NOTE.—All walls with mortar No. 3 were in group 2 and were built by mason C. The rest were in group 1 and were built by mason A, except walls 1-S-2-B, 2-E-2-A, 2-E-2-B, 2-S-2-A, 2-S-2-B and (1+3)-E-2-A, which were built by mason B.

The number of walls built of the various kinds of tiles, constructions, and mortars is given in Table 2. In most cases two similar walls were built, tested in the same manner, and the results averaged. Four similar walls were built in some cases, so that two of them might be tested in compression under central loading and the other two tested in compression under eccentric loading, as will be explained later. Only one wall each of 6–E–2 and 6–E–3 (fig. 3–A) was built. Two walls of 1–M–2 (fig. 6) were built, but one was tested under central loading and one under eccentric loading. Figure 5 shows a group of the tile walls in the laboratory.

(*b*) SIZE.—The walls were 6 feet long, about 9 feet high, and either 8 or 12 inches thick. The nominal thickness and the number of tile courses in the walls are given in Table 2.

(*c*) WORKMANSHIP AND BUILDING CONDITIONS.—A contract for building the walls was let, on a lump sum basis, to a contractor

whose workmen were experienced in hollow-tile construction. Because of the large number of walls to be built it was necessary to divide them into two groups. The first group of 35 walls was built and tested before the construction of the other 35 was commenced.

Two masons were employed on the first group. They were instructed to build the walls in the same manner and with the same care that they would use on a commercial job. No other instructions in regard to workmanship were given them. The tiles for these walls were stored in the laboratory and, consequently, were dry. They were not wetted before, during, or after the construction of the walls. All the walls built with lime mortar, the No. 2 cement-lime mortar, and cement mortar were in this first group.

It was observed that, in general, the side construction walls of the first group had full mortar beds and the ends of the tiles were fairly well "buttered." In the construction of the eccentrically tested walls 1–S–2 and 2–S–2, however, it was noted that the horizontal bedding consisted only of a narrow strip of mortar between the courses about 1½ or 2 inches wide along the faces of the walls. In the end construction walls of this group the longitudinal shells of the tiles were bedded, but no attempt was made to obtain a mortar bearing on the central longitudinal webs. The cross joints between two tiles of the same course were, however, generally covered with mortar, so that a bearing an inch or two long was obtained for these webs at each vertical joint. Figure 7 shows a view of the horizontal bedding of wall 1–E–2–A.

The walls of the second group were all built by a third mason. He was instructed to spread full mortar beds for all side construction walls and to bed carefully the central longitudinal web of the end construction walls. The tiles for this group of walls were stored outdoors, and a hose was used to wet them thoroughly in the late afternoon of the day before they were used. All walls built with the 1C:1¼L:4S (No. 3) cement-lime mortar were in this last group. Thirteen of the tiles in wall 2–S–2–B (eccentrically loaded) had corners broken off. The pieces broken out were from 1 to 3 inches, on an edge. Very few tiles with broken corners were used in any of the other specimens.

The walls were built on steel channels (fig. 6), so that they could be moved into the testing machine. Starting on the level channels, the walls were kept plumb and the courses level as the work progressed.

(*d*) Construction Data.—The construction data for the walls are given in Table 2.

(1) *Rate of building.*—The time required to build each wall was recorded, beginning when the base plate was level and ending when

FIG. 7.—*Mortar bed on end construction walls of the first group*

A portion of wall I-E-2-A. Note that the longitudinal center webs are not in bearing except for a short distance at the cross joints

the last tile was laid. The time, about 10 minutes, required to erect the scaffold was included.

The rate of building the walls with the large tiles was greater than with the small tiles. It will, however, be noted that walls built with the 1C:1¼L:4S (No. 3) cement-lime mortar (that is, by the third mason and with more careful workmanship) were built with a slower rate than were the nearly comparable walls built with the 1C:1¼L:6S (No. 2) cement-lime mortar. It is not believed that this difference was due to the mortar but was probably because different masons built the walls. In fact, there can be no question but that the 1C:1¼L:6S mortar was "shorter" than the 1C:1¼L:4S mortar and, therefore, the use of the former should be expected to increase the mason's time. A direct comparison of the rate of building the walls of lot No. 1 tiles with mortars Nos. 1, 2, and 4 is, however, possible, since they were all built by one mason and from tiles of the same lot. It is seen that the 1C:3S (No. 4) cement mortar walls were built as quickly as those with lime or cement-lime mortars.

(2) *Mortar materials.*—Table 2 shows the amounts of the various mortar materials used for each square foot of wall surface. The amount of water used is reported since it affected the plasticity of the mortar and probably also its strength. In every case for which comparisons can be made the end construction walls required more mortar materials than the corresponding side construction walls.

(*e*) Aging Conditions.—The first 35 walls were built during May and June, 1924, and the rest during October and November of the same year. The walls remained in the laboratory until they were tested. They were not wetted during that time.

(*f*) Age.—The walls were tested from 57 to 65 days after construction.

(*g*) Method of Testing.—(1) *Transverse tests.*—Twenty-seven of the walls were subjected first to a transverse test and then to a compressive test under central loading.

Figure 8 shows wall 13–S–3–B in position for the transverse test. It was restrained from lateral movement at the top as shown and at the bottom by two pins set in the concrete floor against which the channel abutted. The top of the wall was not restrained vertically other than by the steel beam which weighed 5 lbs./in.^{2} gross wall area (equal to a light roof load). The wall was loaded transversely through two horizontal timbers extending its full length. One was 18 inches above and the other 18 inches below the mid height of the wall. The load was distributed equally to the horizontal timbers through a loading timber abutting the hydraulic jack.

The force exerted on the wall was determined from the reading of a pressure gauge attached to the hydraulic pump (not shown) which operated the jack. The deflections of the wall at mid height of each

end were read on mirror scales, graduated to 0.1 inch, by means of fine wires attached near the top and bottom of the wall and kept taut by rubber bands. The load was increased until the wall cracked.

(2) *Compressive tests, central loading.*—The walls were tested in compression in a vertical hydraulic compression machine [3] having a

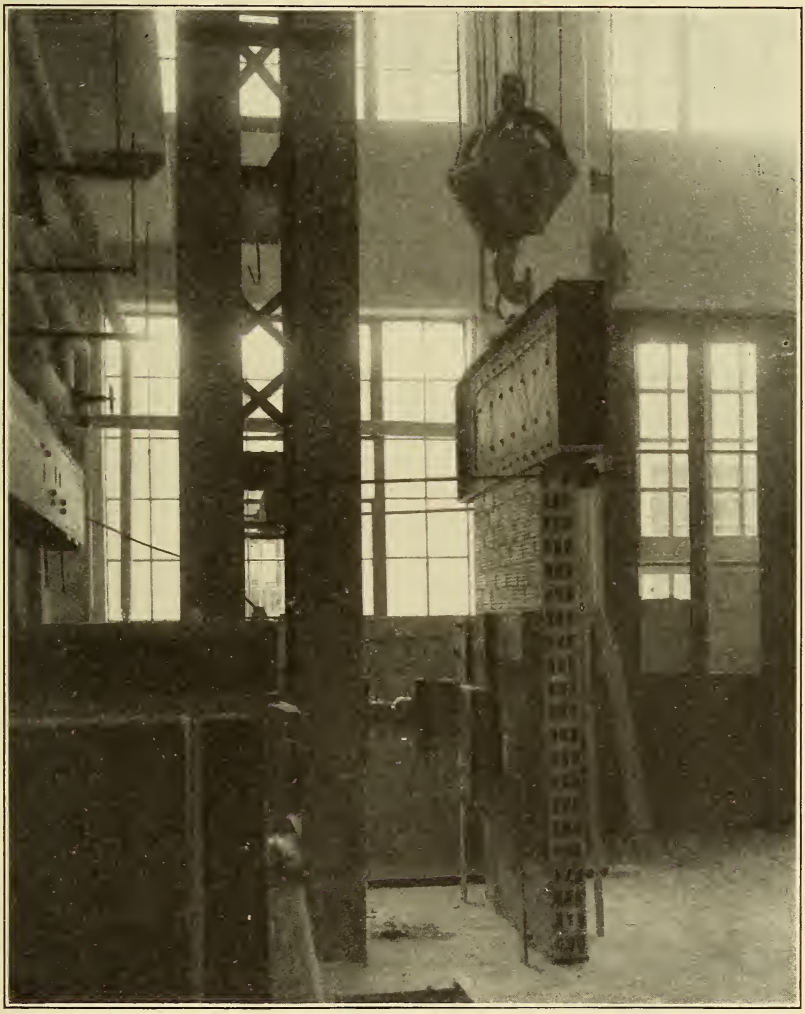

FIG. 8.—*Wall 13–S–3–B in position for the transverse test*

capacity of 10,000,000 pounds. A spherical bearing is part of the lower head of this machine.

Fifty-three walls were tested in compression under central loading. For these tests the channel at the base of the wall was bedded in

[3] For a description of this machine see B. S. Tech. Paper No. 101, Tests of Large Bridge Columns Griffith and Bragg, p. 6

plaster of Paris. A cap of plaster of Paris was then spread on the top of the wall and the upper head of the machine lowered till the space between it and the wall was filled with plaster. Vertical compressometers were attached near each corner, as shown in Figure 9. The gauge length (about 85 to 100 inches) was the height of the wall

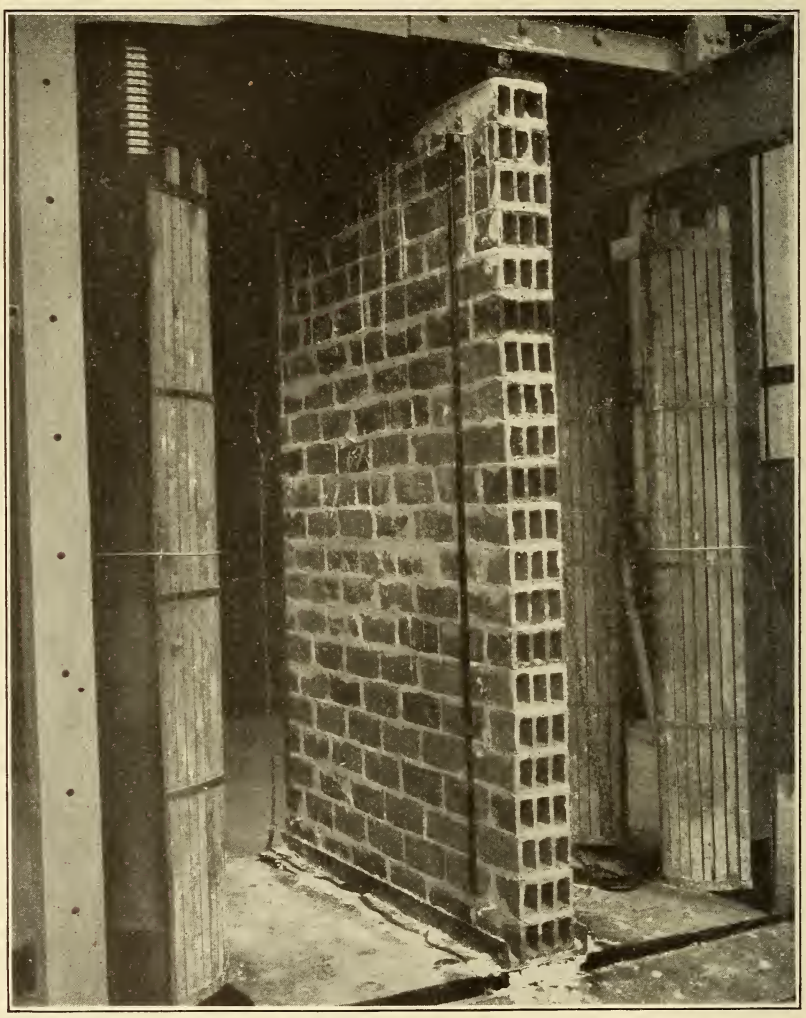

FIG. 9.—*Wall 13–S–3–A in the testing machine ready for the compression test, eccentric loading*

Note the long gauge compressometers

minus the height of two courses of tile. The dial micrometers were read to the nearest one-thousandth of an inch at each 25 lbs./in.^{2} increment of load on the wall (see p. 336).

(3) *Compressive tests, eccentric loading.*—Seventeen walls were tested in compression under eccentric loading. For these tests the upper

head of the machine was raised after the plaster-of-Paris cap had set, and a plane steel plate was placed on the top of the wall. A steel bar 2 inches in diameter was then set on the steel plate, the axis of the bar being parallel to the face and 2 inches from the central plane of the wall. Thus, these walls were tested with a compressive load

FIG. 10.—*Typical failure of end construction tile wall*

Wall 1-E-2-B which had been eccentrically loaded. The white arrows locate the 8-inch gauge lines in the tile courses

having an eccentricity of 2 inches. The compressometer readings were taken in the same manner as for the centrally loaded walls. Figure 9 shows wall 13–S–3–A in the testing machine ready for the compressive test under eccentric loading.

In the eccentrically loaded walls built of tiles whose heights were 12 inches supplementary strain-gauge readings of 8-inch gauge length were taken on both sides of the walls in one tile of each course with the exception of the bottom and top courses. The location of the gauge lines on one side of wall 1–E–2–B is shown in Figure 10 by the white arrows. The gauge lines on the other side of the wall were directly opposite those shown. These strain readings were taken at each 50 lbs./in.^{2} increment of load on the wall.

III. RESULTS OF THE TESTS WITH DISCUSSION

1. BASIS OF COMPUTATIONS

In considering the strength or elastic properties of the tiles a distinction must be made between gross area and net area. For end construction the gross area of a tile is calculated from the maximum width and thickness and for side construction from the thickness and length. For end construction the net area is calculated as the total area of the shells and webs and for side construction as the minimum area of the vertical shells and webs. In all cases measured (not nominal) dimensions were used.

The areas (gross areas) of the walls were calculated from their nominal lengths (72 inches) and nominal thicknesses (8 or 12 inches). All numerical data pertaining to the walls are based upon their gross areas.

2. TILES

The results of the tests of the individual tiles are given in Table 1. Weights and tolerances accepted as *standard are given in Simplified Practice Recommendation No. 12.*[4] The tiles of lot Nos. 5, 8, 9, and 15 were too heavy and those of lot Nos. 7, 10, and 13 were too light in weight according to these standards. The weights of the other tiles were within the prescribed tolerances.

TABLE 3.—*Average strength of mortar specimen s*

Mortar number	Proportions (by volume)	Specimens tested	Average compressive strength	Average tensile strength
			Lbs./in.^{2}	*Lbs./in.*^{2}
1	1¼ L:3S	12	85	14
2	1C:1¼L:6S	81	760	80
3	1C:1¼L:4S	105	1,190	135
4	1C:3S	12	1,990	155

[4] United States Department of Commerce, Elimination of Waste—Simplified Practice, Hollow Building Tile: 1924.

TABLE 4.—*Results of transverse tests of hollow-tile walls*

Wall designation [1]	Wall thickness	Description of tiles and size in inches	Maximum load	Distance between restraints	Equivalent uniform load	Modulus or rupture
	Inches		*Pounds*	*Inches*	*Lbs./ft.²*	*Lbs./in.²*
1-E-1	8	6-cell, 8 by 12 by 12	1,080	106	27	18
1-S-1	8	do	1,970	108	49	39
1-E-2	8	do	2,080	107	52	41
4-E-2	8	do	2,390	105	60	47
1-S-2	8	do	2,900	109	71	62
8-S-2	8	H-shaped, 8 by 10¼ by 12	4,350	92	115	73
1-M-2	8	6-cell, 8 by 12 by 12	1,570	107	39	29
1-E-3	8	do	1,670	107	41	32
5-E-3	8	do	1,980	102	50	36
6-E-3	8	XXX, 8 by 12 by 12	1,980	107	49	39
7-E-3	8	do	2,190	104	55	41
9-E-3	8	Double shell, 8 by 12 by 5	3,320	107	82	70
1-S-3	8	6-cell, 8 by 12 by 12	2,700	109	66	57
4-S-3	8	do	2,080	110	51	44
5-S-3	8	do	1,980	105	50	38
6-S-3	8	XXX, 8 by 12 by 12	2,410	105	60	47
10-S-3	8	2-cell, 8 by 5 by 12	3,010	104	76	60
13-S-3	8	3-cell, 8 by 5 by 12	3,630	103	92	72
14-S-3	8	T-shaped, 8 by 6¼ by 12	1,980	106	49	38
15-S-3	8	do	2,500	108	62	52
1-E-4	8	6-cell, 8 by 12 by 12	2,660	106	66	53
1-S-4	8	do	4,450	109	110	98
2-E-2	12	6-cell, 12 by 12 by 12	5,580	105	140	49
(1+3)-E-2	12	6-cell, 8 by 12 by 12 3-cell, 3¾ by 12 by 12	5,690	106	142	50
2-S-2	12	6-cell, 12 by 12 by 12	6,100	108	151	57
(10+11+12)-S-3	12	Faced with brick	6,100	106	152	55
14-S-3	12	T-shaped, 8 by 6¼ by 12	4,870	106	121	42

[1] The symbols listed in this column represent, in the order used: Tile lot number, construction, and mortar number.

3. MORTAR

The average results of the tests of the mortar specimens are given in Table 3.

4. TRANSVERSE TESTS OF THE WALLS

The results of the transverse tests of the tile walls are given in Table 4. The equivalent uniform loads given in Table 4 were calculated to give a maximum bending moment equal to the bending moment produced between the loads on the assumption that the wall was a simple beam with two line loading. On the same assumption the modulus of rupture was computed, taking account of the axial load equal to the vertical load of 5 lbs./in.² wall area plus the weight of the wall above the line of fracture. The beam section was considered to be a solid rectangle of breadth equal to the length of the wall (72 inches) and of a depth equal to the thickness of the wall (8 or 12 inches). This is, of course, an arbitrary assumption, but the true section modulus of a tile wall is a variable which depends upon the location of the section considered.

The equivalent uniform loads which may, perhaps, be considered as equivalent to wind pressures are, of course, greater for the 12-inch walls than for the 8-inch ones. The failure when the maximum

load was reached always occurred between the mortar and the tiles, never in the mortar bed or in the tiles. The modulus of rupture values, then, are roughly measures of the adhesive strengths between tiles and mortar.

The results of the mortar tests show that the cement-lime mortar 1C:1¼L:4S (No. 3) was stronger than the 1C:1¼L:6S (No. 2) mortar (Table 3), but the adhesion values from the transverse tests are not, on the average, larger for walls built with the 1C:1¼L:4S (No. 3) mortar than for those built with the 1C:1¼L:6S (No. 2) mix. The reason for this may be due to the different moisture content of the tiles in the two groups of walls. The tiles of the walls built with the latter mortar were laid dry; those in the other group had been wetted previous to the construction of the walls

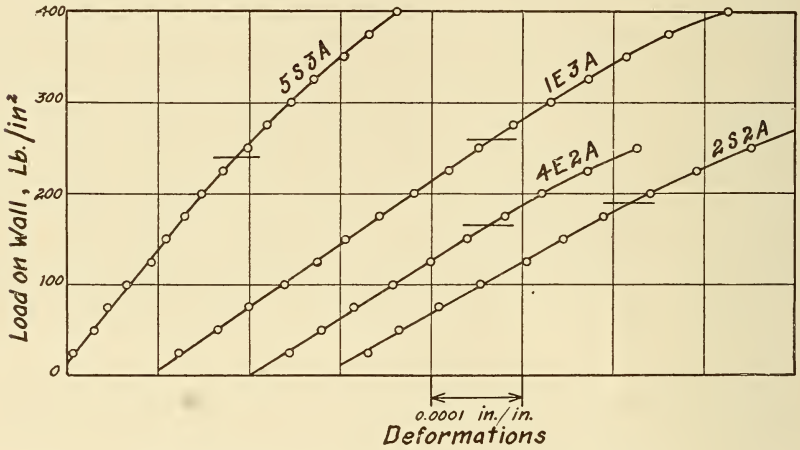

Fig. 11.—*Typical stress-strain curves for the walls*

Evidently the lean mortar (No. 2) used with dry tiles gave about as strong a bond as the rich mortar (No. 3) used with wetted tiles. No other reason is known which might explain why the stronger mortar did not give higher transverse wall strengths. A comparison of the walls built with dry tiles (lot No. 1) shows a marked increase in the modulus of rupture as the cement content is increased. For the end construction walls the values are, for wall 1–E–1, 18 lbs./in.², for wall 1–E–2, 41 lbs./in.², and for wall 1–E–4, 53 lbs./in.², while for the side construction walls the values are, respectively, 39, 62, and 98 lbs./in.².

5. COMPRESSIVE TESTS OF THE WALLS WITH CENTRAL LOADING

(*a*) Deformation of the Walls.—Four typical stress-strain curves are shown in Figure 11. Although these curves had no sudden breaks in slope and showed some curvature throughout their

extent, there was in all of them a stress, approximately half the maximum, at which the curvature showed a sudden marked increase roughly dividing the curves into a lower approximately straight portion and an upper markedly curved portion. The location of this change is shown by a cross line on the curves of Figure 11. The values of the modulus of elasticity which are given in Table 5 were calculated from the approximately straight portion of the stress-strain curves.

The stress-strain curves of the walls which had previously been subjected to the transverse test (specimens B) were very irregular. The crack in the wall due to the previous test (transverse) closed gradually as the load was applied, and the deformations were consequently not proportional to the load. No modulus of elasticity values were calculated from the data of tests of specimens B.

(*b*) Behavior of the Walls Under Load.—In the lime-mortar walls the mortar broke down and squeezed from the horizontal beds to a large extent. The crushing of the mortar in the end construction walls began before loads of 50 lbs./in.^{2} wall area were reached. The crushing of the mortar was followed by the spalling of the tiles at the joints and later by the appearance of vertical cracks in the tiles. In the side construction walls with lime mortar the crushing of the mortar was followed by the cracking of the horizontal shells of the tiles and, as the loads were increased, these cracks extended vertically through the horizontal webs in the interior of the tiles.

The appearance after failure of the end construction walls of 6-cell (*1*, *2*, *4*, and *5*, fig. 1) and of XXX (*6* and *7*, fig. 1) tiles with the stronger mortars was very similar to that of the lime-mortar walls except that the mortar was crushed in only a few cases. Figure 10, which shows the eccentrically loaded wall 1–E–2–B after failure, is representative of the appearance of other end construction walls after central loading.

In the side construction walls with the stronger mortars built of the soft and somewhat laminated tiles of lot Nos. 4, 6, 14, and 15, made of surface clay or open burning fire clay (see Table 1), the vertical shells of the tiles spalled and crushed. The horizontal shells and webs of the other side construction walls containing 2-cell, 3-cell, 6-cell, or H-shaped tiles of harder material, dense burning fire clay or shale (see Table 1), in all cases failed before the vertical shells had shown any signs of spalling. The 2-cell tile walls [(10 + 11 + 12)–S–3] (1-cell tiles being used as fillers) with a brick facing split longitudinally from top to bottom of the walls, the brick headers broke, and many of the horizontal shells of the 2-cell tiles parted as they did in the plain 2-cell tile walls (10–S–3).

Figure 12 shows the double-shell tile wall 9–E–3–A after failure. There was no spalling, and every tile except those of the bottom course was found to be split, as shown in the upper part of the photograph.

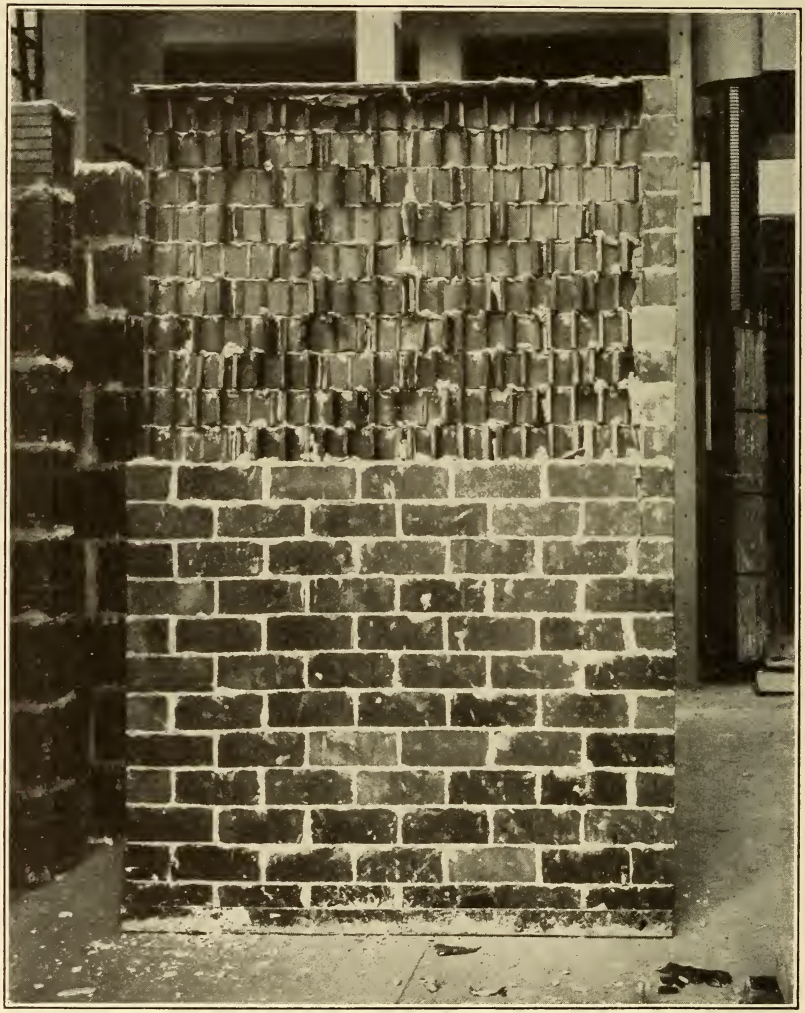

Fig. 12.—*Double shell tile wall 9–E–3–A after failure*

The failure of the walls seemed to be caused, primarily, by the tensile failures of the four transverse webs and shells of each tile (*9*, fig. 1) which connect the double shells near the two wall faces.

(c) Compressive Strength of the Centrally Loaded Walls.—The compressive strength of each of the walls which were centrally loaded is given in Table 5(A). This table is arranged, first, according to wall thickness; secondly, according to mortar number; then, as to construction and finally according to the kind of tiles in the walls. The gross areas of the walls based on nominal thicknesses (8 to 12 inches) and lengths (72 inches) were used in computing the values in this table.

For the centrally loaded walls specimens B had been previously cracked in the transverse loading test. The test results indicate that although the previous test affected the elastic action of the walls it had not lessened the ability of the walls to withstand axial compressive loads. In 10 cases specimen B was stronger than specimen A. In two cases specimens A and B showed equal strength. In 13 cases specimen A was stronger than specimen B. The average strength (excluding the single specimens 6–E–2, 6–E–3, and 1–M–2) of the A specimens was 375 lbs./in.^{2} and that of the B specimens 368 lbs./in.^{2}. The difference 7 lbs./in.^{2} is negligible in comparison with the individual differences.

The results of specimens A and B are considered to be very consistent for masonry tests. In the centrally loaded walls, out of 25 tests, for 16 the discrepancy between the individual tests was not greater than 10 per cent, for 4 between 10 and 20 per cent, and for 4 between 20 and 40 per cent; and of these last, in two cases, 1–S–2 and (1+3)–E–2, the comparison walls were built by different masons. In one case (2–E–2), a 12-inch wall, the A specimen was 79 per cent stronger than the B specimen. It is entirely possible, though by no means certain, that this exceptional discrepancy was due to a weakening of the B specimen in the previous transverse test.

Since the walls differed in so many particulars, it is very difficult to evaluate the effect of workmanship on the strength of a wall. Except for the walls 1–S–2 and (1+3)–E–2, noted above, no comparison can be made between the work of different masons because the third mason used a different mortar. Although the value of Table 5(A) is largely a compilation of data on the strength of tile walls built under commercial conditions, it is worth while to point out the effect of several of the variables on the strength of the walls.

(1) *Effect of mortar.*—The mortar had a greater effect on the strength of these tile walls than any other one factor. Three groups of walls, 1–E—, 1–S—, and 6–E—, gave the most direct comparisons of the effect of the mortar upon wall strength. In each of these groups the tiles and construction were the same, the only difference being differences in mortar and workmanship. In Figure 13 the strength of the walls is plotted as ordinate and compressive strength

TABLE 5.—*Results of compressive tests of hollow-tile walls*

[Walls 6 feet long 9 feet high]

A. CENTRALLY LOADED

Wall designation [1]	Wall thickness	Tiles		Mortar volume ratio	Modulus of elasticity (gross area)	Compressive strength of walls		
		Kind of clay	Description of tiles and size in inches			Specimen A	Specimen B	Average
	Inches				*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
1-E-1	8	Ohio fire clay	6-cell, 8 by 12 by 12	1¼L:3S	150,000	90	90	90
1-S-1	8	do	do	do	278,000	170	160	165
1-E-2	8	do	do	1C:1¼L:6S	660,000	270	280	275
4-E-2	8	New Jersey fire clay	do	do	632,000	290	300	295
6-E-2	8	New Jersey surface clay	XXX, 8 by 12 by 12	do	884,000	370	(2)	370
1-S-2	8	Ohio fire clay	6-cell, 8 by 12 by 12	do	415,000	240	330	285
8-S-2	8	do	H-shaped, 8 by 10¼ by 12	do	803,000	480	430	455
1-M-2	8	do	6-cell, 8 by 12 by 12	do	370,000	200	(2)	200
1-E-3	8	do	do	1C:1¼L:4S	694,000	480	440	460
5-E-3	8	Kentucky shale	do	do	1,076,000	590	510	550
6-E-3	8	New Jersey surface clay	XXX, 8 by 12 by 12	do		(2)	650	650
7-E-3	8	Ohio fire clay	do	do	1,072,000	530	690	610
9-E-3	8	do	Double shell, 8 by 12 by 5	do	1,216,000	540	570	555
1-S-3	8	do	6-cell, 8 by 12 by 12	do	562,000	410	400	405
4-S-3	8	New Jersey fire clay	do	do	340,000	240	220	230
5-S-3	8	Kentucky shale	do	do	1,264,000	490	510	500
6-S-3	8	New Jersey surface clay	XXX, 8 by 12 by 12	do	526,000	230	250	240
10-S-3	8	Ohio fire clay	2-cell, 8 by 5 by 12	do	569,000	380	290	335
13-S-3	8	do	3-cell, 8 by 5 by 12	do	750,000	420	460	440
14-S-3	8	Georgia surface clay	T-shaped, 8 by 6¼ by 12	do	350,000	330	280	305
15-S-3	8	New Jersey surface clay	do	do	536,000	450	410	430
1-E-4	8	Ohio fire clay	6-cell, 8 by 12 by 12	1C:3S	846,000	370	340	355
1-S-4	8	do	do	do	457,000	370	350	360
2-E-2	12	do	6-cell, 12 by 12 by 12	1C:1¼L:6S	850,000	430	240	335
(1+3)-E-2	12	do	6-cell, 8 by 12 by 12 3-cell, 3¾ by 12 by 12	do	870,000	280	360	320
2-S-2	12	do	6-cell, 12 by 12 by 12	do	682,000	370	400	385
(10+11+12)-S-3	12	do	2-cell, 8 by 5 by 12 1-cell, 3¾ by 5 by 12 Faced with brick	1C:1¼L:4S	792,000	560	560	560
14-S-3	12	Georgia surface clay	T-shaped, 8 by 6¼ by 12	do	411,000	360	320	340

B. ECCENTRICALLY LOADED (THE ECCENTRICITY OF LOADING WAS 2 INCHES)

1-E-2	8	Ohio fire clay	6-cell, 8 by 12 by 12	1C:1¼L:6S	605,000	190	170	180
1-S-2	8	do	do	do	513,000	160	120	110
8-S-2	8	do	H-shaped, 8 by 10¼ by 12	do	637,000	230	170	200
1-M-2	8	do	6-cell, 8 by 12 by 12	do		(2)	110	110
1-E-3	8	do	do	1C:1¼L:4S	723,000	330	320	325
10-S-3	8	do	2-cell, 8 by 5 by 12	do	544,000	240	240	240
13-S-3	8	do	3-cell, 8 by 5 by 12	do	606,000	200	290	245
2-E-2	12	do	6-cell, 12 by 12 by 12	1C:1¼L:6S	515,000	180	140	160
2-S-2	12	do	do	do	342,000	120	160	110

[1] The symbols listed in this column represent, in the order used: Tile lot number, construction, and mortar number.

[2] Wall not built.

NOTE.—The modulus of elasticity values for the centrally loaded walls are for specimens A only. The modulus of elasticity values for the eccentrically loaded walls are the averages from the two walls of each set.

of the mortars as abscissa. The composition of the mortars is also shown.

There was different, and probably better, workmanship for walls built with the 1C:1¼L:4S (No. 3) cement-lime mortar than for the other walls (see p. 330), but it would seem that this would have less effect on the side construction walls fully bedded than on the others. The increase in strength, however, of the side-construction walls 1–S–3 over 1–S–2, both built of the same tiles but with different mortar, although not as great as for the end construction walls 1–E–3 over 1–E–2, is also marked.

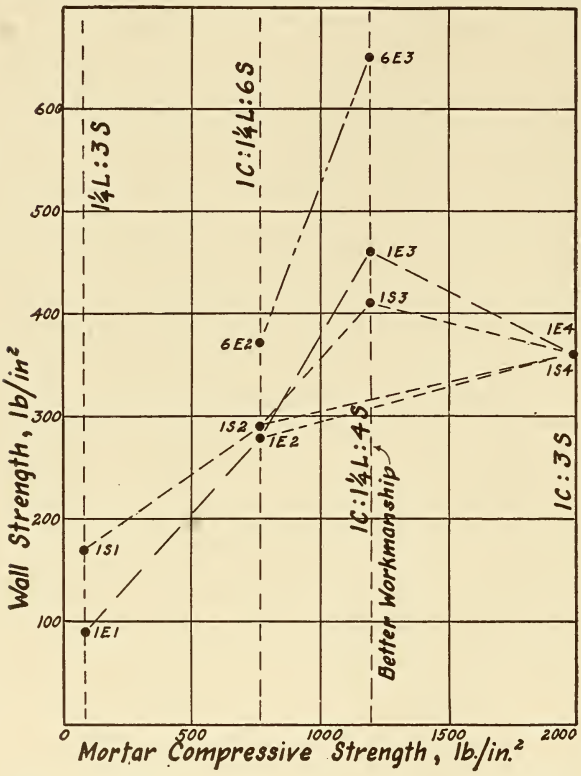

Fig. 13.—*Relation between wall strength and mortar strength*

The lime mortar walls were all very low in strength; those built with end construction failed at less than 100 lbs./in.² wall area.

It is important to note that the strongest walls were obtained, not with the mortar which had the highest compressive strength, but with the mixture that contained the least amount of sand relative to the cementing materials, cement and lime. The difference in the strength of the walls of the first and second groups was not due entirely, however, to the mortars used. In the end construction walls of the first group there was no mortar bearing on the central longitudinal webs of the tiles, while for those in the second group these webs were bedded. This accounts, at least in part, for the higher strength of the end construction walls of the second group with the 1C:1¼L:4S mortar over those of the first group with the stronger 1C:3S mortar. Of the walls built with the same relative amount of cementing materials and sand those were strongest which contained the most cement. Comparisons of the strength of

the walls built with 1C:1¼L:4S (No. 3) mixture with those built of lime mortar (No. 1) show that for the same labor cost the walls built with the richer mortar are from 2.4 to 5.1 times as strong. Since the increase in the cost of the mortar materials for the mortar producing the stronger walls is but a small percentage of the total cost of a hollow tile wall, it is evident that the strength of the wall may be materially increased with a small additional expenditure for these materials. The increase in strength of the 1C:1¼L:4S mortar walls over those of the 1C:1¼L:6S is also marked.

(2) *Effect of wall construction, end, side, and mixed.*—Figure 14 compares the strength of end construction walls with otherwise identical side construction walls. Thus, the point marked 6–3 has for ordinate the compressive strength of the end construction wall 6–E–3 and for abscissa the average compressive strength of the side construction walls 6–S–3. If a point, as 1–4, lies on the 45° line through the origin, the strengths of end (1–E–4) and side (1–S–4) construction walls of this kind were on the average the same. If it lies above this line (as 1–3), the end construction walls 1–E–3 were on the average stronger than the side construction walls 1–S–3. For points lying below the 45° line the side construction walls were the stronger.

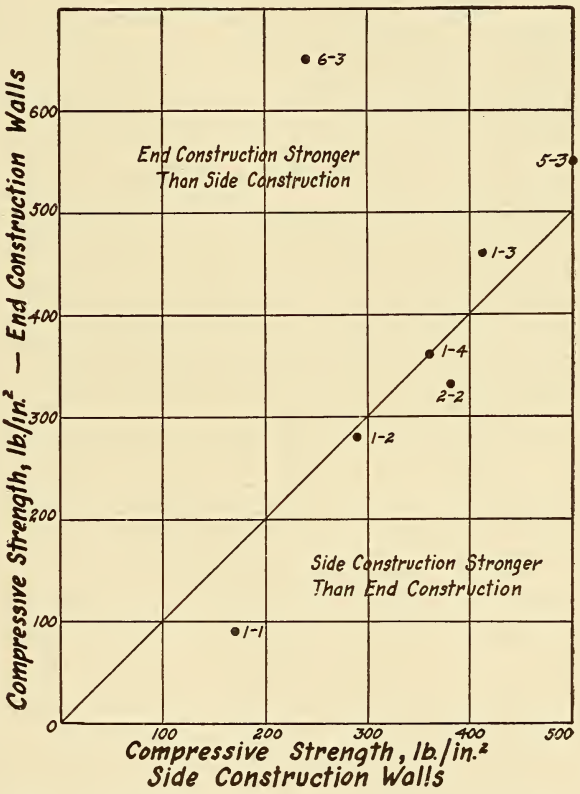

Fig. 14.—*Relation between the strength of end construction and side construction walls*

The comparison made in Figure 14 is between end construction walls and side construction walls constructed with tiles designed for use in end construction. No comparisons are available between end and side construction walls of tiles designed for side construc-

tion, since with most of these it is not feasible to use them in end construction.

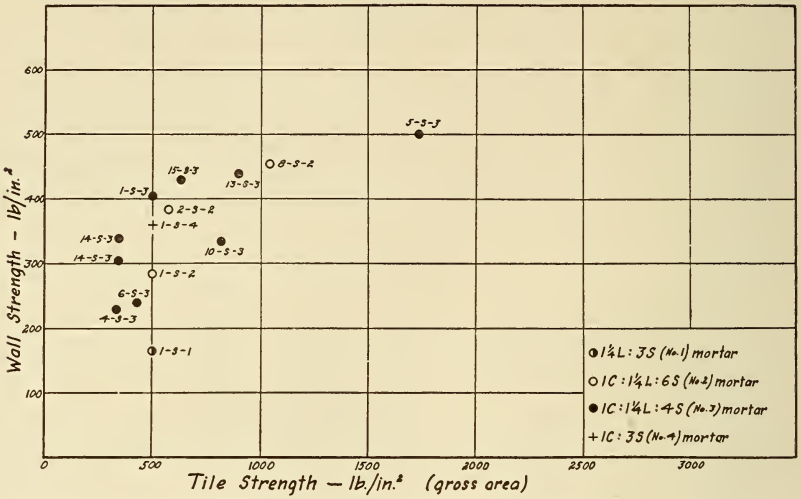

FIG. 15.—*Relation between the strength of the side construction walls and the strength of the tiles*

It is seen that the end construction walls are stronger only for those cases in which the rich 1C:1¼L:4S mortar (No. 3) and careful workmanship were used. While, as may be seen from values of

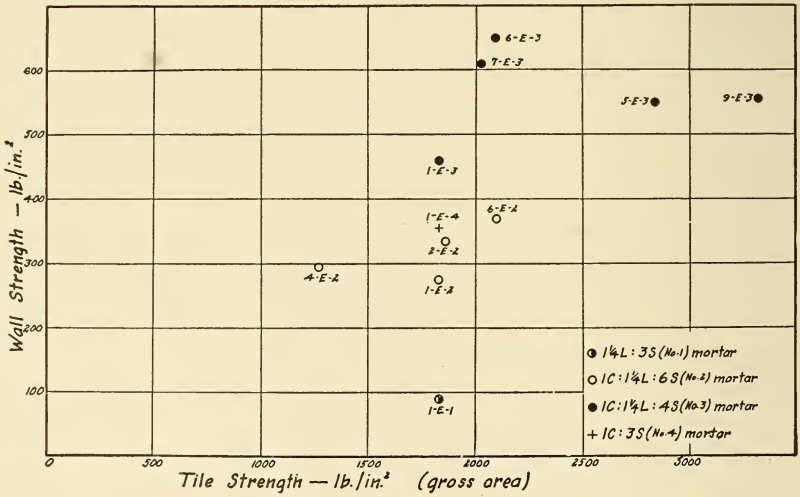

FIG. 16.—*Relation between the strength of the end construction walls and the strength of the tiles*

net areas of the tiles in Table 1, there is a much greater net area in a tile available for compression in end than in side construction walls, it is evident that this larger net area does not necessarily make

the end construction stronger. That an increase in strength corresponding to the greater net area does exist for carefully built end construction walls is proved by the tests reported by Whittemore and Hathcock.[5]

The strength of the mixed construction walls (fig. 6), in which each alternate tile had its cells horizontal and the cells of the other tiles were vertical, was found to be less than for either the end or side construction walls built of tiles of lot No. 1. The strength values are 280, 290, and 200 lbs./in.^{2} for walls 1–E–2, 1–S–2, and 1–M–2, respectively.

(3) *Effect of strength of the single tiles.*—The relation between the strength of the walls and the strength of the tiles is shown in Figure 15 for the side construction walls and in Figure 16 for the end construction walls. Because of the many variables—tiles, wall construction, and mortar—and the few cases in which direct comparisons can be made, it is impossible to accurately predict the strength of the walls from a knowledge of the tile strength. With the 1C:1¼-L:6S (No. 2) mortar, the strength of the end construction walls seemed to be quite independent of the strength of the tiles. With the 1C:1¼L:4S (No. 3) mortar the stronger tiles, in general, produced the stronger walls. Walls 4–S–3 and 6–S–3 had the lowest strength of any of the side construction walls built with the No. 3 mortar.

TABLE 6.—*Comparison of wall strength with wall thickness and tile design*

Wall designation	Source and kind of clay	Mortar	Construction	Thickness of wall	Tiles		Strength of walls
					Lot number	Design	
				Inches			*Lbs./in.^{2}*
8–S–2	Ohio fire clay	1C:1¼L:6S	Side	8	8	H-shaped	455
2–S–2	do	do	do	12	2	6-cell	385
1–S–2	do	do	do	8	1	do	285
2–E–2	do	do	End	12	2	do	335
(1+3)–E–2	do	do	do	12	(1+3)	do 3-cell	320
1–E–2	do	do	do	8	1	6-cell	275
(10+11+12)–S–3	do	1C:1¼L:4S	Side	12	(10+11+12)	2-cell 1-cell Brick	560
13–S–3	do	do	do	8	13	3-cell	440
1–S–3	do	do	do	8	1	6-cell	405
10–S–3	do	do	do	8	10	2-cell	335
7–E–3	do	do	End	8	7	XXX	610
9–E–3	do	do	do	8	9	Double shell	555
1–E–3	do	do	do	8	1	6-cell	460
14–S–3	Georgia surface clay.	1C:1¼L:4S	Side	12	14	T-shaped	340
14–S–3	do	do	do	8	14	do	305

These walls were built of tiles designed primarily for use in end construction, and some features of their designs are not adapted for

[5] See footnote 1, p. 318.

side construction. On account of the grooves in the 8-inch faces of the No. 4 tiles it was not feasible in side construction to obtain a mortar bearing for the central longitudinal webs. In walls 4–S–3 the central longitudinal webs were not in bearing. There were similar, though smaller, grooves in the faces of the No. 6 tiles which probably caused an imperfect bearing for the central longitudinal webs of walls 6–S–3. The unequal spacing of the transverse webs of the No. 6 tiles may also have lessened their ability to withstand loads in side construction.

The average strengths of each set of side construction walls built of tiles having a compressive strength greater than 500 lbs./in.^{2} and with 1C:1¼L:4S mortar were in all cases greater than 330 lbs./in.^{2}. The average strengths of each set of end construction walls built with 1C:1¼L:4S mortar were in all cases greater than 450 lbs./in.^{2}.

As may be seen from Figures 15 and 16, the ratio of wall strength to tile strength was not constant, but varied with the mortar, the wall construction, and the strength and design of the tiles. The values of this ratio covered such a wide range (0.05 for walls 1–E–1 to 1.00 for the 12-inch walls 14–S–3) that they appear to have no useful meaning.

(4) *Effect of thickness of the walls and design of the tiles.*—In Table 6 a comparison is made between all groups in which the material (tile and mortar) and the construction (end and side) were the same. Five comparable groups are shown. In each group the walls differ only in thickness and design of the tiles, the only exception being the brick-faced walls (10+11+12)–S–3. Thickness of the walls can not be separated, in general, from the design of the tiles except for the walls of T-shaped tiles (14–S–3) (see fig. 4, *D*, *E*) the units of which the 12-inch walls were constructed were at least in part different from those used in the 8-inch walls. However, all the 12-inch walls were stronger, measured in lbs./in.^{2} wall areas, than any 8-inch walls in the same group excepting those of H-shaped tiles. The exception is marked, the 8-inch walls of H-shaped tiles (8–S–2) averaging 18 per cent stronger than the 12-inch 6-cell (2–S–2) and 55 per cent stronger than the more nearly comparable 8-inch 6-cell (1–S–2).

There are two reasons why the H-shaped tile walls might be expected to be stronger than those built of 6-cell tiles. The ratio of net area to gross area was greater (0.31 and 0.23, respectively) for the former and the distances between the vertical shells and webs were less, thus lessening the bending moments produced in the horizontal shells. In the middle group it is evident that walls built of 3-cell tiles were considerably stronger than were the 2-cell tile walls. The greater strength of the 3-cell tile walls might also have been expected for the same reasons given for the H-shaped tiles.

The walls 7–E–3 shown in the fourth group (Table 6) and the walls 6–E–3 (see Table 5) built of XXX tiles were the strongest sets of walls of the entire series. With this design of tile used in end construction, it is possible by careful workmanship to place the transverse webs of each tile vertically above the shells of the tiles immediately below it. In the walls tested this was done. It seems certain that the greater bearing area thus secured accounts almost wholly for the high strength of these walls, since the ratio of net area to gross area of the XXX tiles No. 7 (0.39) was even less than for the 6-cell tiles No. 1 (0.41). The higher strength of the walls with double shell tiles (9–E–3) is probably due wholly to the greater net area of the tiles, since the ratio of wall strengths compared with the 6-cell (1–E–3) 1.22 is only slightly greater than the ratio of net area of the tiles in the wall (1.18) for the two tiles (9 and 1).

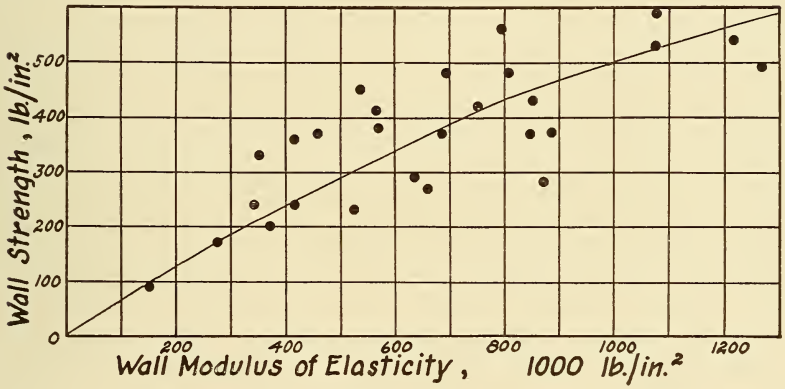

Fig. 17.—*Relation between the strength and the modulus of elasticity of the walls*

(*d*) Relation Between the Strength and the Modulus of Elasticity of the Walls.—In Figure 17 the strengths of the centrally loaded walls are compared with their moduli of elasticity. It is evident that the modulus of elasticity is, in general, greater for the stronger walls, but the values are too scattering to enable a prediction of the wall strength to be made from its modulus of elasticity.

6. COMPRESSIVE TESTS OF THE WALLS WITH ECCENTRIC LOADING

(*a*) Deformations in the Walls.—(1) *Modulus of elasticity in the walls.*—The moduli of elasticity for the eccentrically loaded walls are given in Table 5(B). These values were determined as for the centrally loaded walls from the average shortening indicated by the compressometers shown in Figure 9. The moduli of elasticity of the eccentrically loaded walls agree well with values determined from the similar walls centrally loaded except for the walls 2–E–2 and 2–S–2.

These were built by different masons, and in addition (see p. 330) the eccentrically loaded walls 2–S–2 did not have full horizontal mortar beds.

(2) *Variation of deformations in walls with height.*—If a wall is centrally loaded, compressive deformations in a tile should be expected to be equal on both sides of the wall. If, however, the wall is eccentrically loaded, the deformations will be larger in that side of the tile which is nearer to the loading bar. It is also reasonable to suppose that the load distribution across the wall, which is not uniform at the top of the wall due to the manner of loading (see fig. 9), might become more uniform at lower heights. Strain-gauge readings in both sides of the same tile and in tiles of different courses were taken to ascertain how the deformation distribution varied with the height. Since the loading bar was always placed 2 inches east of the longitudinal center plane of the eccentrically loaded walls, the deformations were greater on the east side than in the same tile on the west side. The ratio of these deformations—west ÷ east values—were calculated for loads of 50, 100, and 150 lbs./in.^{2} wall area in all cases in which the data were taken. The average of this ratio for these three loads was then computed for each wall and finally the average ratio for each course of tiles for all the walls. These final average values are plotted in Figure 18 against the course number (proportional to the height above the bottom of the wall). While there is a tendency for the ratio to increase as the bottom of the wall is approached, showing that the effective eccentricity decreased toward the bottom, the average value of the ratio, 0.4, at 1½ feet from the bottom of the wall, indicates that the load was still not uniformly distributed at that height.

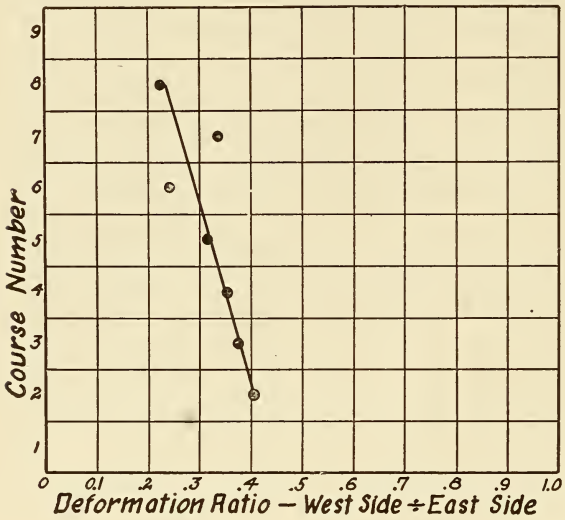

Fig. 18.—*The variation with height, in eccentrically loaded walls, of the average deformation ratios on the two sides of the wall*

The deformations were measured in 8-inch gauge lengths in the tiles as shown in Figure 7

(3) *Apparent eccentricity from compressometer data.*—An apparent eccentricity has been calculated from the long-gauge compressometer

data for the various specimens by the ordinary theory [6] for eccentric loads on prisms and on the assumption that a horizontal section of the wall was a solid rectangle having a depth equal to the thickness of the wall. These values are given in Table 7. It is seen that the average values are slightly greater than 1 inch.

TABLE 7.—*Effective eccentricity (inches) computed from long-gauge compressometer readings of eccentrically loaded walls*

Wall designation	Load (lbs./in.²)			Wall designation	Load (lbs./in.²)		
	50	100	150		50	100	150
	Inches	*Inches*	*Inches*		*Inches*	*Inches*	*Inches*
1-E-2-A	0.68	0.98	1.10	2-S-2-B	1.07		
1-E-2-B	.58	.71	.88	8-S-2-A	1.39	1.51	
1-S-2-A	1.28			8-S-2-B	.97	.97	0.91
1-S-2-B	1.04			10-S-3-A	.98	1.01	.93
1-E-3-A	1.64	1.29	1.07	10-S-3-B	.95	1.02	1.04
1-E-3-B	1.70	1.43	1.34	13-S-3-A	1.06	1.11	1.11
2-E-2-A	.91	.93	1.30	13-S-3-B	.83	.76	.75
2-E-2-B	1.47	1.20					
2-S-2-A	1.01			Average	1.10	1.08	1.04

In these tests the lower head of the testing machine, even with its spherical bearing, acted as if the lower end of the wall had flat end conditions. This was probably due to the large mass of this platen (about 18 tons) and the relatively small torque tending to cause its readjustment under the load. The action line of the resultant of the forces, therefore, probably extended from the center of the loading bar to the center of the base of the wall. Such conditions would give an eccentricity at mid height of the wall of 1 inch, practically the same as the average value computed from the long-gauge compressometers.

(*b*) COMPRESSIVE STRENGTH OF THE ECCENTRICALLY LOADED WALLS.—The compressive strength of the eccentrically loaded walls given in Table 5 (B) was less than of those loaded centrally. This is probably due partly to the different end conditions. The average values are plotted in Figure 19 against the strengths of similar walls centrally loaded. As has already been noted, the eccentrically loaded walls 1–S–2 and 2–S–2 did not have full horizontal mortar beds while the centrally loaded walls did. This, of course, may account for the relatively low values with eccentric loading. The average loads supported by walls with eccentric loading were about 60 per cent of those supported by similar walls with central loading.

[6] Merriman, Mechanics of Materials, John Wiley & Sons, New York, p. 214; 1916.

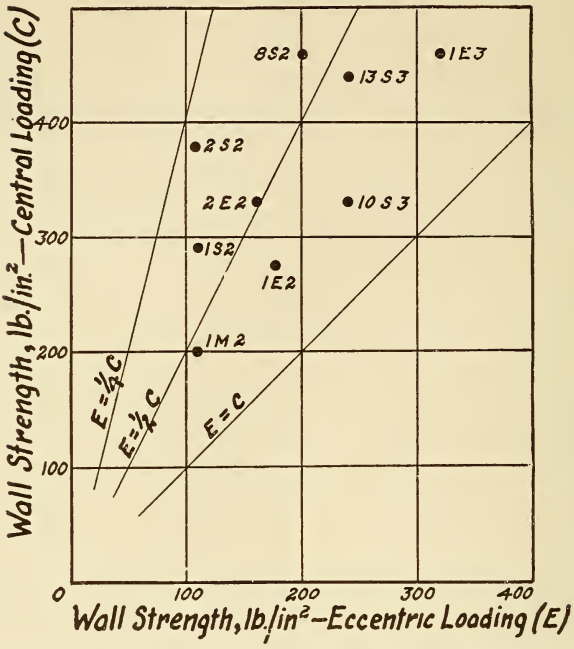

FIG. 19.—*The relation between the strengths of the centrally loaded and the eccentrically loaded walls*

IV. CONCLUSIONS

The results of these tests of 70 hollow-tile walls, built of various grades and designs of tiles, with different constructions and mortars, and with ordinary workmanship under average indoor conditions, lead to the following conclusions:

1. The compressive strengths, lbs./in.² gross area, of these tile walls varied between the values:

Mortar	Number of walls	Construction	
		End	Side
Lime (1¼L:3S)	4	90–90	160–170
Cement-lime (1C: 1¼L:6S)	15	240–430	240–480
Cement-lime (1C: 1¼L:4S)	29	440–690	220–510
Cement (1C:3S)	4	340–370	350–370

2. The mortar seemed to be the most important factor affecting the compressive strength of the walls, the differences in average strength of each set of two walls built of 6-cell, 8 by 12 by 12 inches, Ohio fire-clay tiles with different mortars, taking the lime mortar wall strengths as unity, were:

Mortar	Construction	
	End	Side
Lime (1¼L:3S)	1.0	1.0
Cement-lime (1C:1¼L:6S)	3.1	1.7
Cement-lime (1C:1¼L:4S)	[1] 5.1	[1] 2.4
Cement (1C:3S)	4.0	2.1

[1] As noted on p. 330, the walls with the 1C:1¼L:4S mortar were built by a different mason and probably more carefully than those with the other mortars. Mortar was spread on the longitudinal webs of the end construction walls with the 1C:1¼L:4S mortar; with the other walls these webs were not in bearing.

3. The average strengths of each set of side construction walls built of tiles having a compressive strength of more than 500 lbs./in.^{2} and with 1C:1¼L:4S mortar were in all cases greater than 330 lbs./in.^{2}. The average strengths of each set of end construction walls built with 1C:1¼L:4S mortar were in all cases greater than 450 lbs./in.^{2}.

4. The values of the ratio of wall strength to tile strength covered such a wide range (0.05 to 1.00) that they appear to have no useful meaning.

5. The end construction walls were stronger than the side construction walls only when built with rich mortar and with the central longitudinal webs of the tiles in bearing.

6. On the average the loads supported by the eccentrically loaded walls were 60 per cent as great as those supported by the similar walls centrally loaded.

7. The results of the transverse tests show that the 8-inch walls resisted side pressures equivalent to 30 to 115 lbs./ft.^{2} and the 12-inch walls side pressures of 120 to 150 lbs./ft.^{2}. With other conditions the same, the walls with the stronger mortars had the greater transverse strength.

WASHINGTON, October 3, 1925.