RP–108

COMPRESSIVE STRENGTH OF CLAY BRICK WALLS

By A. H. Stang, D. E. Parsons, and J. W. McBurney

ABSTRACT

Compressive tests of 168 walls of common brick, each 6 feet long and about 9 feet high and of 129 wallettes, about 18 inches long and 34 inches high, were made. Four kinds of brick, 3 mortar mixtures, 2 grades of workmanship, different curing conditions, and 10 different types of masonry (3 solid and 7 hollow) were the variables.

Wall strengths were more closely related to the shearing strength of the single brick than to any other strength property of the brick. On the average, the compressive strength of the wallettes was by far a better measure of the strength of the walls than any of the brick strength values. The use of cement mortar gave higher wall strengths than of cement-lime mortar and much higher than if lime mortar was used. For the solid walls the strength varied about as the cube root of the compressive strength of the mortar cylinders, 2-inch diameter and 4-inch length, cured on the walls. Large differences in strength due to differences in workmanship were found. The walls having smoothed-off spread-mortar beds and filled joints were much stronger than walls in which the horizontal mortar beds were furrowed by the mason's trowel. Some of this difference in strength might be ascribed to difference in the filling of the vertical joints. Some of the walls laid in cement mortar were kept damp for seven days after construction. These walls were not stronger than similar walls cured under ordinary conditions in the laboratory.

The solid walls were stronger than the hollow types. With bricks of rectangular cross section the hollow wall strengths varied about as the net areas in compression. When the bricks were not truly rectangular in section, the strength of the hollow walls was found to be less than that expected from the net area. Construction data are given which show the relative saving in materials and time for the hollow types. The results of the wallette tests confirm, in general, the conclusions deduced from the wall tests.

CONTENTS

I. INTRODUCTION

At a conference held at the Bureau of Standards in 1921, attended by representatives of the clay, sand-lime, and cement brick industries, it was agreed that the bureau should make tests which would afford a comparison of the strength of masonry built of these three kinds of brick.

Tests of walls built of sand-lime brick have been made and the results reported in Technologic Paper No. 276. The present paper reports and discusses the results of the tests on clay brick masonry. In this report walls numbered 1 to 17 are of such construction as to permit comparison with those built of sand-lime brick, but it should be noted that the sand-lime brick used were of slightly higher compressive strength than those used in the construction of walls 1 to 17, inclusive. The effect of brick strength on wall strength is discussed herein. The tests on masonry of cement brick have not yet (1929) been made.

The scope of this investigation has been extended much beyond the original plan, for it seemed desirable to discover, if possible, some of the factors which influence or measure masonry strength. It is believed that much pertinent information, not heretofore known and analyzed, has been disclosed and that this information may be useful to engineers and architects and to the construction industry generally.

The present construction trend is toward a more economical use of material, but it is obvious that a handicap is imposed upon any structural material if the "factor of uncertainty" is large. Brick masonry has been under such a handicap in the past, for few tests have been made on specimens which fairly represent brick walls as used in construction. Tests of brick masonry made heretofore have been principally of piers and small wall sections, and results have not been conclusive for two reasons: (1) Uncertainty has existed as to the relationship between the stress producing failure in these small specimens and that in brick walls as used in structures; (2) previous reports have given but little data on the effect of the various physical properties of individual bricks, and especially on the effect of workmanship on wall strength.

Realizing these conditions, the Bureau of Standards, cooperating with the Common Brick Manufacturers' Association of America, undertook the investigation reported herein.

II. SCOPE AND PURPOSE OF THE TESTS

This investigation deals with the compressive tests under central loading of 168 brick walls each 6 feet long and about 9 feet high and of 129 wallettes or small walls each about 18 inches long and 34 inches high. A view of several of the walls in the laboratory is shown in Figure 1. Four kinds of common brick, three mortar mixtures, and ten types of wall construction were included. Table 1 gives the wall numbers for the different variables.

TABLE 1.—*Wall specimens*

Type of wall	Mortar	Wall numbers and kind of brick						
		Series 1			Series 2			
		Chicago	Mississippi	New England	Chicago	Detroit	Mississippi	New England
8-inch solid	Lime	1, 2, 3						
	Cement-lime	7, 8, 9				19, 20, 21	34, 35, 36	94, 95, 96.
	Cement	13, 14, 15	155,[1] 159 [1]	154 [1]	160,[1] 161,[1] 162,[1] 163,[1] 164,[1] 165.[1]	22, 23, 24	37, 38, 39	97, 98, 99.
	Cement-wetted					33		
12-inch solid	Lime	4, 5, 6						
	Cement-lime	10, 11, 12				25, 26, 27	40, 41, 42	100, 101, 102.
	Cement	16, 17			166,[1] 167,[1] 168 [1]	28, 29, 30	43, 44, 45	103, 104, 105.
	Cement-wetted					31, 32	46, 47	106, 107.
	Cement-shoved				18		48	108.
8-inch all-rolok	Cement-lime						49, 50, 51	109, 110, 111.[1]
	Cement		156 [1]				52, 53, 54	112, 113, 114.
12-inch all-rolok	Cement-lime						55, 56, 57	115, 116, 117.[1]
	Cement						58, 59, 60	118, 119, 120.[1]
8-inch all-rolok in Flemish bond	Cement-lime						61, 62, 63	121, 122, 123.[1]
	Cement		157 [1]				64, 65, 66	124, 125, 126.[1]
12-inch all-rolok in Flemish bond.	Cement-lime						67, 68, 69	127, 128, 129.[1]
	Cement						70, 71, 72	130, 131, 132.[1]
8-inch rolok-bak	Cement-lime						73, 74, 75	133, 134, 135.[1]
	Cement		158 [1]				76, 77, 78	136, 137, 138.[1]
12-inch rolok-bak (heavy duty)	Cement-lime						79, 80, 81	139, 140, 141.[1]
	Cement						82, 83, 84	142, 143, 144.[1]
	Cement-wetted						85, 86	145, 146.
12-inch rolok-bak (standard)	Cement						87	147.[1]
4-inch Economy	Cement-lime						88,[1] 89,[1] 90 [1]	148,[1] 149,[1] 150.[1]
	Cement						91,[1] 92,[1] 93 [1]	151,[1] 152,[1] 153.[1]

[1] No wallette built with these walls.

The walls are divided into two series based on the grade of workmanship. A contract for building the walls of series 1 was let on a lump-sum basis to a brick mason who specialized in small contracts and who laid the bricks for all walls in the series. The walls of series 2 were built under rather careful supervision by a mason who was hired by the day.

It is hoped that the data obtained from these tests will be valuable for the purposes listed below.

1. To determine the relation between the several physical properties of the bricks and the strength of walls built therefrom.
2. To obtain the comparative strengths of different types of solid and of hollow walls of brick.
3. To determine the effect of damp curing on the compressive strength of brick walls.
4. To determine the relation between the strength of the mortar and the strength of the wall.
5. To determine the effect of the quality of workmanship on wall strength.
6. To compare the compressive strengths of masonry specimens of different sizes.

III. DESCRIPTION OF SPECIMENS AND THE TESTING METHODS

1. BRICKS

(a) DESCRIPTION OF THE BRICKS

Four kinds of common bricks were used in building the specimens for this investigation. As the principal differences between these bricks are in the method of manufacture, a short description of the methods of forming is here introduced.

Bricks are usually formed by the soft-mud, dry-press, or stiff-mud processes. In the soft-mud process the clay is reduced with water to a semiliquid consistency and formed in molds with slight pressure. Usually the molds are first dampened and then sanded before use, thus giving the bricks a finish which is commonly termed "sand struck." The dry-press process resembles the soft-mud process except that much less water is used, resulting in a stiffer mixture, and the bricks are formed in molds under considerable pressure. In the stiff-mud process the clay mixture is extruded from an orifice or die in a continuous column which is cut to form the individual bricks. If the cross section of the column is approximately 8 by 3¾ inches and the cuts are 2¼ inches apart, there results what are known as "side-cut" bricks. If the column has a cross section approximately 2¼ by 3¾ inches and the cuts are 8 inches apart, the term "end-cut" is applied to the bricks. Sometimes double or triple dies are used on one machine, but the columns are cut in the same manner as when but one is used.

For convenience these bricks are designated by the name of the region in which they were made and are described as follows:

Chicago.—These bricks were made from surface clay and formed by the end-cut, double-column, stiff-mud process. They are rather irregular in shape and contain lime nodules.

Detroit.—These bricks were formed by the soft-mud process from surface clay. Like many soft-mud bricks, they were formed with a frog or depression in one face approximately 0.4 inch deep. These Detroit bricks resemble the soft-mud bricks from the Cleveland (Ohio) region.

Mississippi.—These were surface-clay bricks formed by the dry-press process. Regularity of size and shape was the outstanding characteristic of these specimens.

New England.—These bricks were formed by the soft-mud process from surface clay and were "sand struck." The specimens possessed a shallow frog or depression, were very hard burned, and rather irregular in size and shape.

The average sizes and weights of these bricks, from measurements of 50 specimens of each kind, are given in Table 2.

TABLE 2.—*Average size and weight of the bricks*

Kind of brick	Chicago	Detroit	Mississippi	New England
Length .... inches..	7.84	8.16	8.20	7.88
Width .... do....	3.60	3.60	3.80	3.54
Thickness .... do....	2.21	2.46	2.34	2.24
Dry weight per brick .... pounds..	3.94	4.16	4.20	4.56
Weight .... pounds per cubic foot..	109	99	99	126

(b) TEST METHODS

The usual tests as outlined by the American Society for Testing Materials,[1] of compressive strength, modulus of rupture, and water absorption, were made on about 50 bricks of each kind. In order to obtain a more complete knowledge of the properties of the brick, still other tests were carried out as outlined below.

(1) COMPRESSIVE TESTS.—The compressive tests of half bricks on edge are the only tests described in the specifications for building brick of the American Society for Testing Materials. It was decided, however, to include also compressive tests of whole bricks edgewise and flatwise. Besides the half bricks tested flatwise and edgewise in a dry condition, an equal number of half bricks were tested when wet. For these tests they were prepared as for the dry tests, immersed

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[1] A. S. T. M. Standards, p. 665; 1924.

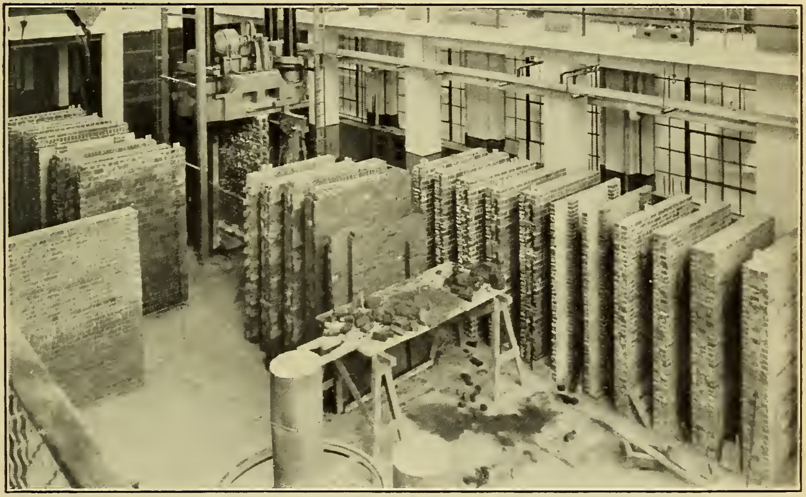

FIGURE 1.—*Brick walls stored in the laboratory*

Note the mortar specimens on the walls.

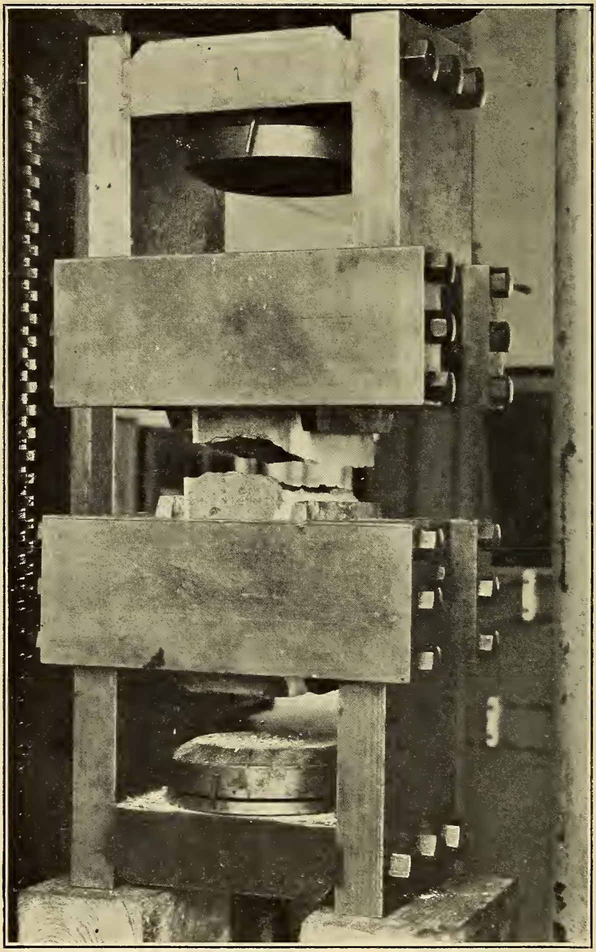

FIGURE 2.—*Apparatus for tensile tests of brick*

in water at room temperature for 48 hours, taken out, and tested within 10 minutes.

The compressive strength was obtained by dividing the maximum load by the sectional area.

(2) Transverse Tests.—The bricks for the transverse test were tested on a 7-inch span with a central load and with apparatus recommended by the American Society for Testing Materials. Since in some of the walls the bricks are laid on edge or rowlock, transverse tests were made on brick edgewise as well as flatwise. The modulus of rupture in pounds per square inch was computed from the formula

$$R=\frac{3}{2}\frac{wl}{bd^2}$$

in which

l is the distance between supports, 7 inches,

b is the width of the brick perpendicular to the line of load application, in inches,

d is the depth of the brick parallel with the line of load application, in inches, and

w is the maximum center load in pounds.

(3) Tensile Tests.—Tensile tests of the whole brick were made in the apparatus [2] shown in Figure 2. The bricks for these tests were dried and shellacked. The sides of the bricks were than bedded in plaster of Paris to give smooth and parallel surfaces as shown in this figure. The spherical bearings of the apparatus assisted in producing a uniform loading over the cross section of the specimen, and nearly all of the specimens broke in the free length between the ends of the gripping wedges.

The tensile strength was obtained by dividing the maximum load by the product of the width and depth of the brick.

(4) Shear Tests.—Punching shear tests were made with the apparatus designed by H. H. Dutton and described and pictured in Kessler and Sligh's paper on "Physical Properties of the Principal Commercial Limestones Used for Building Construction in the United States." [3] All tests except those on the New England brick were made on halves from the tensile test. Due to the strength of the New England brick, it was found necessary to use thinner test specimens, and consequently the tests were made with slabs 1 inch in thickness sawed from whole bricks.

(5) Absorption Tests.—Water-absorption tests were made by the 5-hour boiling test and by a 48-hour immersion test. For the former, dry bricks were submerged in water at room temperature, the water

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[2] For a more complete description of this apparatus, see J. Am. Ceram. Soc., **11**, No. 2, pp. 114-117; February, 1928.

[3] D. W. Kessler and W. H. Sligh, B. S. Tech. Paper No. 349, p. 508.

heated to boiling within 1 hour, boiled continuously for 5 hours, and allowed to cool to room temperature. In the 48-hour immersion test they were immersed in water at room temperature for that period of time. The percentage of absorption was calculated on the dry weight according to the relation

$$\text{Percentage of absorption} = 100\frac{(B-A)}{A}$$

where A is weight of the dry brick and B is the weight of the saturated brick.

2. MORTAR

The mortar mixes represent certain commonly used volume proportions. Measurements 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 weights 94 pounds. The weight of the dry materials in a cubic foot, loose measure, of the damp sand used on this work was determined by preliminary tests to be about 73 pounds. Since the weight of a cubic foot of damp sand, loose measure, varies with the moisture content, the moisture in 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 mortar for walls 1 to 18 and 160 to 162, built of Chicago brick, was mixed in the same proportions as had been used for the sand-lime brick walls, already referred to. These mixtures were as follows:

Lime mortar	By volume, 1¼ parts of hydrated lime to 3 parts of damp sand; weight equivalents, 50 pounds of lime to 220 pounds of dry sand.
Cement-lime mortar	By volume, 1 part of Portland cement, 1¼ parts of hydrated lime, to 6 parts of damp sand; weight equivalents, 94 pounds of cement, 50 pounds of lime, to 440 pounds of dry sand.
Cement mortar	By volume, 1 part of Portland cement to 3 parts of damp sand; weight equivalents, 94 pounds of cement to 220 pounds of dry sand.

The mortar mixtures used in the other walls were cement lime and cement mortars. They differed slightly from the above mixes so as to be in conformity with the mortars recommended for solid walls by the Building Code Committee of the Department of Commerce.[4]

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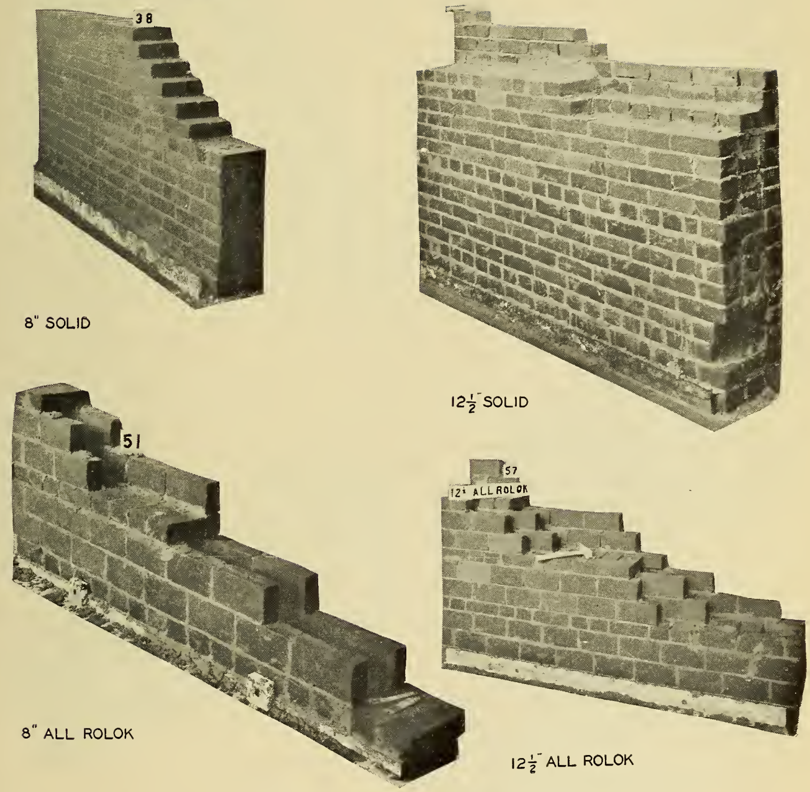
[4] Report of Building Code Committee, Elimination of Waste Series, Recommended Minimum Requirements for Masonry Wall Construction, Department of Commerce, Washington, D. C.



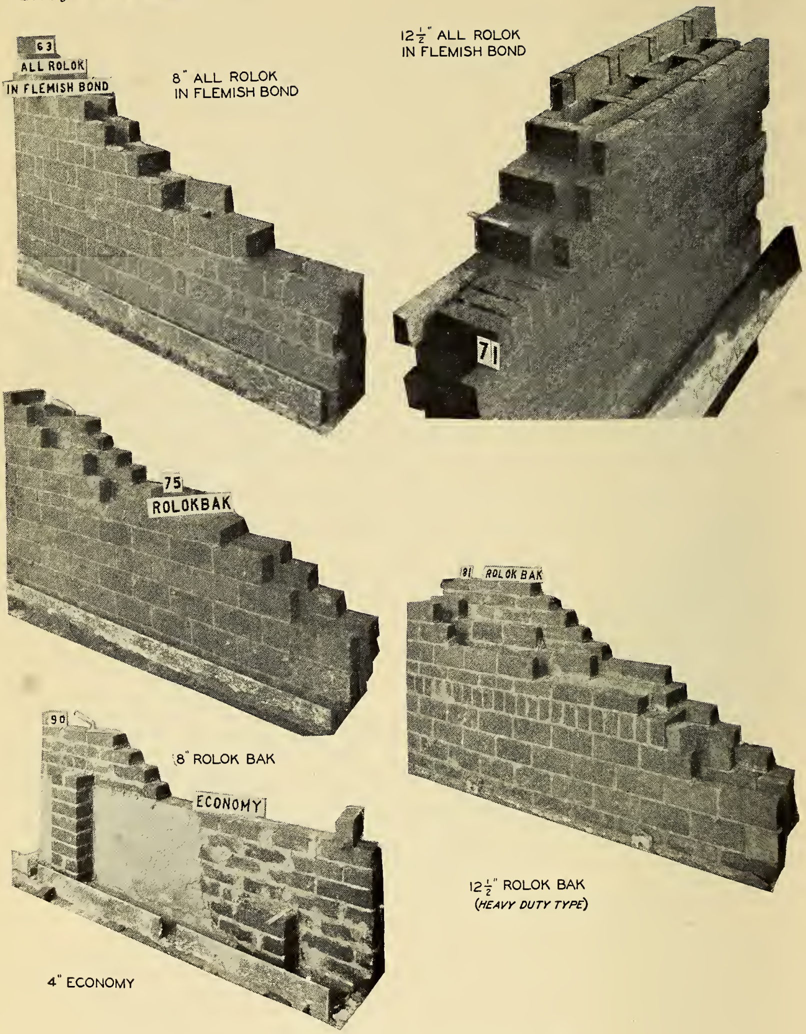
8" SOLID

$12\frac{1}{2}$" SOLID

8" ALL ROLOK

$12\frac{1}{2}$" ALL ROLOK

FIGURE 3.—*Types of brick walls*



8" ALL ROLOK IN FLEMISH BOND

12½" ALL ROLOK IN FLEMISH BOND

8" ROLOK BAK

12½" ROLOK BAK (*HEAVY DUTY TYPE*)

4" ECONOMY

FIGURE 4.—*Types of brick walls*

The mixtures for walls 19 to 159 and 163 to 168 were as follows:

Cement-lime mortar	By volume, 1 part of Portland cement, 1 part of hydrated lime, to 6 parts of damp sand; weight equivalents, 94 pounds of cement, 40 pounds of lime, to 440 pounds of dry sand.
Cement mortar	By volume, 1 part of Portland cement to 3 parts of damp sand (hydrated lime equal to 10 per cent of the volume of the cement was added); weight equivalents, 94 pounds of cement, 4 pounds of lime, to 220 pounds of dry sand.

It is not believed that these mortars differed to an appreciable extent in their effect on brick-wall strength from the corresponding mortars used in the walls of Chicago brick, but a comparison of the cement mortars may be obtained from the results of tests of the two groups, 160 to 162 and 163 to 165.

The Portland cement and the hydrated lime were purchased on the open market and conformed to the requirements of the United States Government purchase specifications, Federal Specifications Board specification Nos. 1a and 249, respectively. The sand was Potomac River sand. All the lime and sand were on hand before any walls were built. The cement was obtained as needed from Government-inspected bins.

Six cylinders (2 inches diameter, 4 inches long) for compressive tests were made from the mortar of each wall, except that for each wall built with lime mortar only three cylinders were made. After they had been taken from the molds, three cylinders were placed on the wall they represented, as shown in Figure 1, and allowed to age in this position. These cylinders will be described as "dry." The other cylinders were placed in water and will be termed "wet." The three cylinders made for each of the lime mortar walls were aged dry because lime mortars disintegrate when placed in water. The cylinders were tested on the same day as the corresponding wall.

3. WALLS

(a) TYPES

Ten different types of brick masonry were included in this investigation. They consisted of three types of solid brickwork, and seven types of hollow walls as follows:

A, 8-inch solid.
B, 12-inch solid.
C, 8-inch all-rolok.
D, 12-inch all-rolok.
E, 8-inch all-rolok in Flemish bond.
F, 12-inch all-rolok in Flemish bond.
G, 8-inch rolok-bak.
H, 12-inch rolok-bak, heavy duty.
I, 12-inch rolok-bak, standard.
J, 4-inch economy walls.

Partially completed walls of each of these types, except that of the 12-inch rolok-bak, standard type, are shown in Figures 3 and 4. Sectional views of the 10 types of construction are shown in Figure 5.

The 8-inch and the 12-inch solid walls were laid in common American bond, having headers each sixth course. The bricks in these walls were laid flat. These types are shown in Figure 3.

The solid walls built with Chicago brick (walls 1 to 18) began and ended with a header course. None of the other solid walls had header courses at the top or bottom.

The hollow walls had header courses at the top and bottom. In the all-rolok walls the stretchers are laid on edge. Every third course is a header course with the brick flat. Figure 3 shows that in the 8-inch all-rolok wall the headers are side by side and, of course, extend completely through the wall. The back of a 12-inch wall of this type is also shown in Figure 3. The center withe of brick on edge is not centered in this wall, but is lined up with the outside headers as shown in Figure 5. The header courses are of "basket weave," in which two header bricks joining the face withe with the central withe alternate with two header bricks joining the back withe with the central withe, the spaces opposite each pair of headers being occupied by a single stretcher.

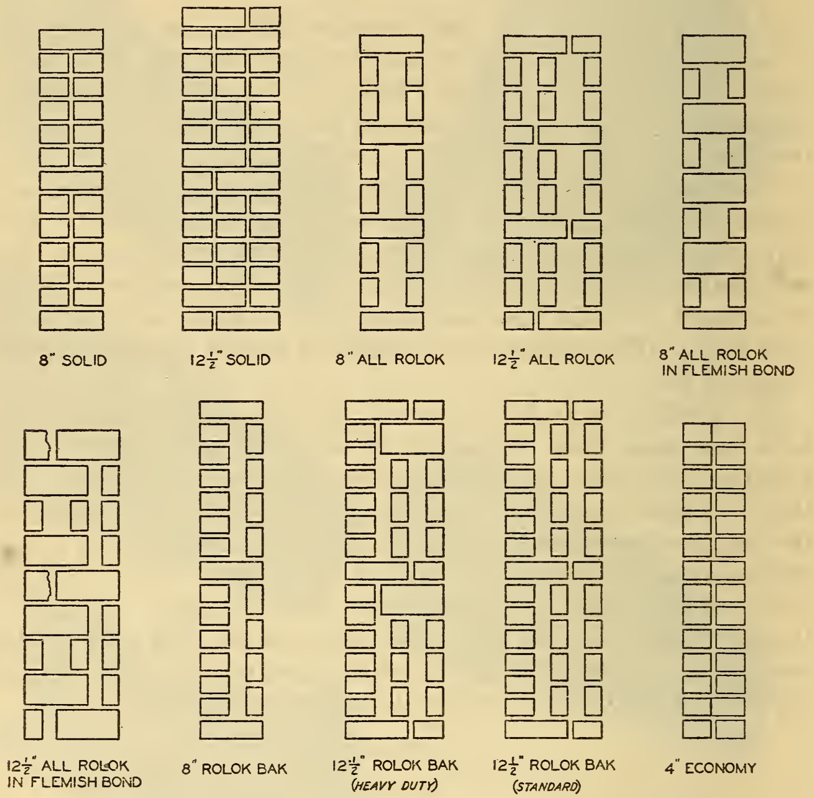

8" SOLID
12½" SOLID
8" ALL ROLOK
12½" ALL ROLOK
8" ALL ROLOK IN FLEMISH BOND
12½" ALL ROLOK IN FLEMISH BOND
8" ROLOK BAK
12½" ROLOK BAK (HEAVY DUTY)
12½" ROLOK BAK (STANDARD)
4" ECONOMY

Figure 5.—*Sectional views of the types of brick-wall construction tested*

The all-rolok in Flemish bond walls are shown in Figure 4. In these walls all the bricks are on edge laid in Flemish bond for the outside 8-inch width. For the 12-inch wall a withe of stretchers is added, three courses high. The appearance of the front of the wall in the next course is still of the Flemish bond, but the headers of this course are bats and the backing is a continuous course of rowlock headers.

The exterior 4-inch thickness of the rolok-bak walls, shown in Figure 4, is laid with the brick flat and the backing is laid of brick on edge. On the exterior, therefore, the brickwork has the usual appearance of ordinary brickwork having headers each seventh course. Four courses of brick on edge bring the backing courses to the same height as that of the six flat courses of the face. The 12-inch rolok-bak wall, shown in Figure 4, is the heavy-duty type recommended by the Common Brick Manufacturers' Association for heavy load-bearing construction. In this type the fourth backing course consists of rolok-headers. Two 12-inch rolok-bak walls, standard type, were included in this investigation. The standard type differs from the heavy-duty type by having the four backing courses all stretchers, the flat header course being of "basket weave." This difference is shown in Figure 5.

The economy wall shown in Figure 4 is essentially a 4-inch wall with pilasters 8 inches wide and 4 inches thick built into the wall at intervals of about 5½ stretcher lengths. The pilasters were tied to the 4-inch withe with headers each sixth course. All bricks were laid flat. The "economy" walls of this investigation were plastered on the back between the pilasters with the same kind of mortar as that in which they were laid, since this method of construction is recommended for weatherproofing the single withe.

A more extended description of the hollow walls is given in the literature of the Common Brick Manufacturers' Association.[5]

(b) SIZE

The walls were 6 feet long. When necessary, the end bricks were chipped so as to project only slightly beyond the end of the wall, as shown in Figure 1. The height of the walls was about 9 feet.

The thickness of each wall was measured at three different heights on each end and was considered as the average of these six measurements. The length of each wall was considered to be 72 inches, since this was their minimum length and equaled the lengths of the base channels and the platen of the testing machine.

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[5] Hollow Walls of Brick and How to Build Them, Common Brick Manufacturers' Association of America, Cleveland, Ohio.

(c) WORKMANSHIP

The walls of this investigation have been divided into two series, each of which was built by a different mason and with a different grade of workmanship. There is at present no scale by which the workmanship can be measured, and, consequently, differences in the quality of the work are difficult to evaluate. The following description may aid in judging the grades of workmanship.

(1) Series 1.—Walls 1 to 17 of series 1 were built so as to have the quality of the workmanship directly comparable to that obtained with the sand-lime brick walls which had already been tested at the Bureau of Standards.[6] Bids were obtained from a number of reputable local masons, and the work of building the walls was awarded the lowest bidder, who happened to be the same mason who had built the sand-lime brick walls. This mason received neither instruction nor supervision. Only on wall 159 of series 1 were instructions given and supervision exercised. Characteristics of the work were that there was practically no mortar in the longitudinal vertical joints, the horizontal mortar beds were deeply furrowed, and the brick were laid at a high rate. Figure 6 is an end view of several walls of series 1.

Figure 7 shows a horizontal mortar bed of one of these walls after the test of the wall. The furrows made by the trowel point are plainly visible, and the uneven bedding caused by them must have weakened the wall. Figure 8 shows an end view of a similar wall built with cement-lime mortar. The trowel marks may be plainly seen. In this connection, it should be pointed out that the mason thought that he eliminated the furrows by pressing down and tapping the brick.

Walls 154 to 158 were built by the same mason and with the same grade of workmanship. The hollow brick walls included among these were the first of those types that this mason had built. Wall 159 was also built by the same person. For this wall he was instructed to fill the vertical mortar joints between the withes and not to furrow the horizontal mortar beds with the point of the trowel.

(2) Series 2.—The walls of series 2 were built by the other mason, who was employed by the day without regard to output. His work was characterized by complete filling of all vertical joints and smoothing of beds. The filling of vertical joints was accomplished not by the use of "shoved" work but by heavy "buttering" and "slushing" or "dashing" after completion of the course. His original instructions were to use his best workmanship without "shoving" the brick. Near the end of the program he was instructed to use shoved work on the two 12-inch solid walls 48 and 108. It may be of interest to note that he did not require instructions in filling vertical joints, but he

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[6] Whittemore and Stang, Compressive Strength of Sand-Lime Brick Walls, B. S. Tech. Paper No. 276

FIGURE 6.—*End view of several walls of series 1*

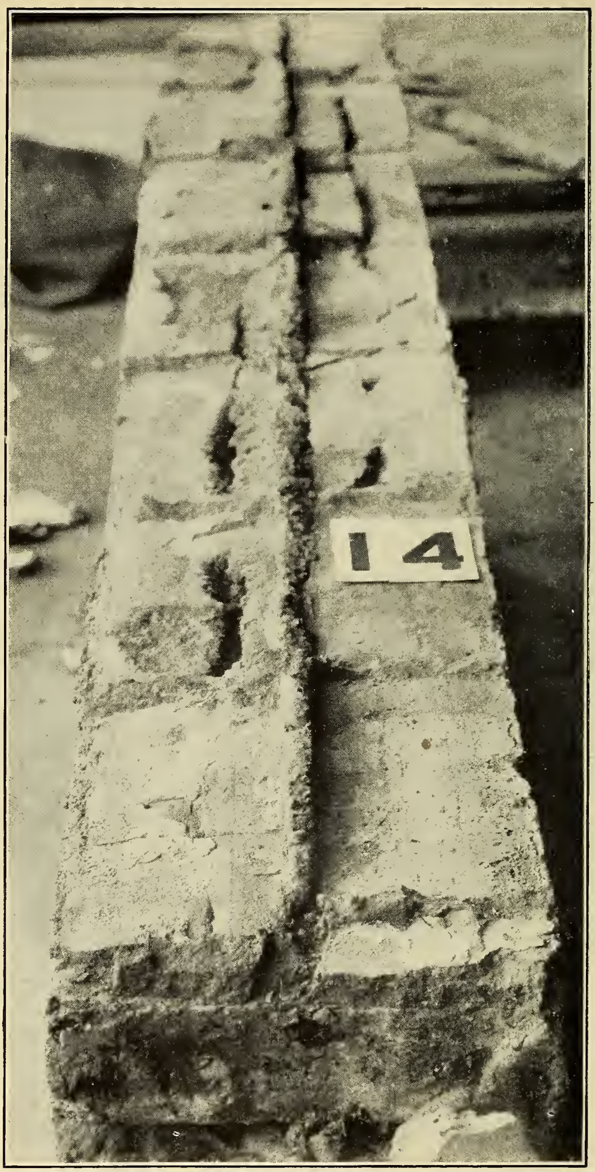

FIGURE 7.—*The mortar bed in a wall of series 1*

Wall 14, an 8-inch solid wall built of Chicago brick, laid in cement mortar.

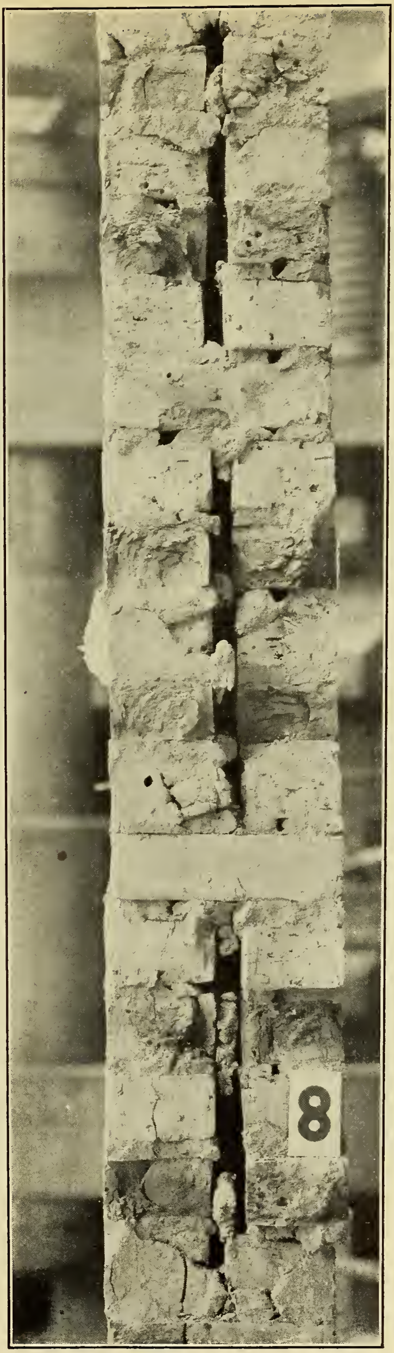

FIGURE 8.—*End view of a wall of series 1 after test*

Wall 8, an 8-inch solid wall built of Chicago brick, laid in cement-lime mortar.

FIGURE 9.—*End view of several walls of series 2*

FIGURE 10.—*The mortar bed in a wall of series 2*

Wall 101, a 12-inch solid wall built of New England brick, laid in cement-lime mortar.

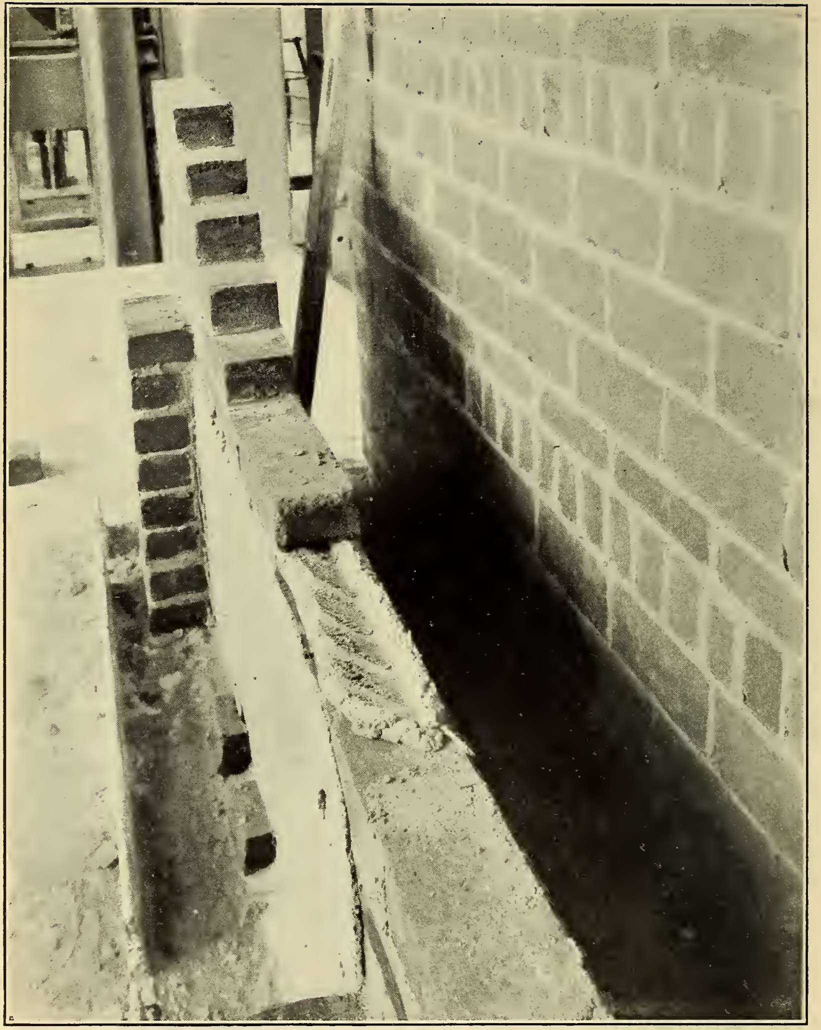

Figure 11.—*Characteristics of the horizontal mortar bed (the furrowing) in the walls of series 1*

FIGURE 12.—*Carefully leveled horizontal mortar beds in the walls of series 2*

FIGURE 13.—*A portion of wall 18 after test*

Note that the mortar joints are completely filled.

had to be cautioned not to furrow the horizontal beds. However, he later reported that laying smooth spread beds was as easy as laying furrowed ones. He worked at all times very carefully and slowly; in fact, his work would be characterized as "fussy" compared with that of the mason who built the walls of series 1. No difference was noted between the general plumbness of the two men's work.

Figure 9 shows an end view of several walls and Figure 10 a typical mortar bed for the walls for series 2. Figures 11 and 12 are views showing a furrowed bed and a carefully leveled horizontal bed.

It was originally planned to have 18 walls of Chicago brick built in series 1, but sufficient bricks were not available to build the last wall (wall 18). Enough bricks were, however, salvaged from the specimens after the tests of the first 17 walls for another wall. Wall 18 was, therefore, built afterwards by the mason of series 2. He used great care in its construction, and it is doubtful whether better construction could have been obtained. Figure 13 shows a portion of this wall after test and gives an idea of how well all joints were filled.

Two 12-inch solid brick walls of this series laid in cement mortar (walls 48 and 108) were built with "shoved" workmanship. Wall 48 was built of Mississippi brick and wall 108 of New England brick. The object of building these walls was to compare the strength of the shoved work with that of equally careful work not shoved.

The difference in the rate of laying brick by the two masons is believed to be due more to the characteristics of the men than to the methods employed. The reason for this belief is that the mason who built the walls of series 1 worked as fast on the supervised wall (No. 159) as he did on the others.

(d) METHOD OF CONSTRUCTION

The Chicago brick used for walls 1 to 18 were stored in the laboratory and were consequently rather dry. The bricks were placed in a wheelbarrow and a pail of water poured over them. On the average, the brick of these walls were drier when laid than those in the other walls.

The other bricks were piled in the open without arranging them in regular order. Twenty-four hours before they were laid in the wall they were thoroughly sprinkled until the water flowed continuously from every portion of the pile. They were again sprinkled in the same manner just before laying.

Each wall was built on a steel channel, as shown in Figure 6, so it could be moved into the testing machine. Starting on the level channel, the wall was kept plumb and the courses level as the work progressed.

(e) CONSTRUCTION DATA

The average construction data for the walls are given in Table 3. The walls were constructed under careful supervision as to the mixture of the mortar materials and records were kept of the time and materials required. Since these records give construction data which may be used in making estimates for comparing the cost of the several types of walls, it is thought that they are of value to contractors and architects.

(1) Rate of Building.—The time required to build each wall was recorded, beginning when the base plate was level and ending when the last brick was laid. The time, about 10 minutes, required to erect the scaffold, was included. Table 3 gives the rate of building in square feet of wall surface per hour per mason and also the rate of laying brick per hour. This table shows that the walls of series 1, which were built under contract, were built at a much faster rate than those of series 2, built by day labor under careful supervision.

TABLE 3.—*Average construction data of brick walls*

A. WALLS OF SERIES 1

Type of wall	Mortar	Kind of brick	Wall Nos.	Average thickness of mortar joints	Rate of building wall	Number of brick laid per hour	Brick per square foot of wall surface	Mortar materials used (pounds per square foot of wall surface)			
								Cement	Lime	Sand (dry)	Water
				Inch	*Sq.ft.hr.*						
8-inch solid	Lime	Chicago	1, 2, 3	0.55	14.4	183	12.7	----	3.2	14.3	4.8
	Cement-lime	do	7, 8, 9	.55	15.4	195	12.6	3.0	1.6	14.4	4.4
	Cement	do	13, 14, 15	.56	14.1	175	12.4	6.0	----	13.9	4.1
		Mississippi	155	.73	17.4	195	11.2	5.0	.2	11.8	5.8
		do	159	.62	19.5	264	13.5	7.2	.3	16.9	6.1
		New England	154	.46	15.0	189	12.6	6.1	.3	14.2	4.9
12-inch solid	Lime	Chicago	4, 5, 6	.55	11.9	226	19.0	----	5.0	22.6	8.3
	Cement-lime	do	10, 11, 12	.56	11.2	212	18.9	4.9	2.6	23.5	7.1
	Cement	do	16, 17	.56	11.6	221	18.9	8.6	----	20.6	6.2
8-inch all-rolok	do	Mississippi	156	.66	19.2	168	8.7	3.2	.1	7.4	2.9
8-inch all-rolok in Flemish bond	do	do	157	.65	17.5	155	8.9	5.2	.2	12.2	----
8-inch rolok bak	do	do	158	.62	20.5	206	10.0	3.7	.2	8.8	----

B. WALLS OF SERIES 2

Type of wall	Mortar	Kind of brick	Wall Nos.	Average thickness of mortar joints	Rate of building wall	Number of brick laid per hour	Brick per square foot of wall surface	Cement	Lime	Sand (dry)	Water
8-inch solid	Cement-lime	Detroit	19, 20, 21	0.41	8.0	94	11.7	3.8	1.6	18.0	5.5
		Mississippi	34, 35, 36	.47	7.7	95	12.3	3.3	1.4	15.3	4.3
		New England	94, 95, 96	.30	7.7	104	13.5	2.7	1.1	12.9	4.4
	Cement	Chicago	160, 161, 162	.57	9.1	118	12.9	7.9	----	18.4	6.2
		do	163, 164, 165	.62	8.8	115	13.1	7.8	.3	18.4	6.1
		Detroit	22, 23, 24, 33	.40	8.2	96	11.7	7.4	.3	17.3	5.6
		Mississippi	37, 38, 39	.45	7.2	89	12.4	5.7	.3	13.4	4.3
		New England	97, 98, 99	.28	7.2	98	13.7	5.3	.2	12.4	4.2
12-inch solid	Cement-lime	Detroit	25, 26, 27	.40	5.8	101	17.4	6.1	2.4	27.3	8.2
		Mississippi	40, 41, 42	.45	6.1	113	18.6	4.6	2.0	21.7	7.4
		New England	100, 101, 102	.26	5.6	117	21.3	5.1	2.2	24.0	6.1
	Cement	Chicago	18	.31	6.4	127	20.0	10.0	----	23.3	7.5
		do	166, 167, 168	.51	6.2	123	19.9	11.0	.4	25.7	8.8
		Detroit	28, 29, 30, 31, 32	.39	6.6	116	17.7	10.4	.5	24.3	7.7
		Mississippi	43, 44, 45, 46, 47, 48	.42	5.2	97	18.7	8.1	.3	19.0	6.0
		New England	103, 104, 105, 106, 107, 108.	.25	5.6	115	20.8	8.8	.4	20.5	6.7

TABLE 3.—*Average construction data of brick walls*—Continued

B. WALLS OF SERIES 2—Continued

Type of wall	Mortar	Kind of brick	Wall Nos.	Average thickness of mortar joints	Rate of building wall	Number of brick laid per hour	Brick per square foot of wall surface	Mortar materials used (pounds per square foot of wall surface)			
								Cement	Lime	Sand (dry)	Water
				Inch	*Sq.ft.hr.*						
8-inch all-rolok	Cement-lime	Mississippi	49, 50, 51	0.43	9.1	84	9.2	1.6	0.7	7.4	2.9
		New England	109, 110, 111	.35	8.5	87	10.2	1.8	.8	8.6	2.3
	Cement	Mississippi	52, 53, 54	.42	10.4	97	9.4	2.8	.1	6.5	2.1
		New England	112, 113, 114	.36	9.0	92	10.2	3.1	.1	7.1	2.3
12-inch all-rolok	Cement-lime	Mississippi	55, 56, 57	.44	7.4	103	13.8	2.3	1.0	10.9	3.4
		New England	115, 116, 117	.36	6.6	100	15.1	2.6	1.1	12.0	3.3
	Cement	Mississippi	58, 59, 60	.44	7.1	99	14.0	4.7	.2	11.1	3.6
		New England	118, 119, 120	.40	5.8	87	14.9	4.8	.2	11.3	3.6
8-inch all-rolok in Flemish bond	Cement-lime	Mississippi	61, 62, 63	.43	10.6	99	9.3	1.6	.7	7.5	2.4
		New England	121, 122, 123	.40	8.7	89	10.2	1.6	.7	7.6	2.3
	Cement	Mississippi	64, 65, 66	.44	10.3	96	9.4	3.0	.1	7.0	2.0
		New England	124, 125, 126	.39	8.6	87	10.1	3.1	.1	7.3	2.5
12-inch all-rolok in Flemish bond	Cement-lime	Mississippi	67, 68, 69	.45	6.9	100	14.5	2.2	.9	10.4	3.2
		New England	127, 128, 129	.43	6.2	99	16.0	2.5	1.1	11.8	3.8
	Cement	Mississippi	70, 71, 72	.44	7.9	115	14.6	4.7	.2	10.9	3.6
		New England	130, 131, 132	.42	5.3	85	16.0	4.5	.2	10.5	3.3
8-inch rolok-bak	Cement-lime	Mississippi	73, 74, 75	.41	9.7	103	10.7	1.8	.7	8.3	2.7
		New England	133, 134, 135	.32	7.7	89	11.6	2.0	.9	9.3	2.9
	Cement	Mississippi	76, 77, 78	.46	8.3	88	10.5	3.4	.1	7.9	2.5
		New England	136, 137, 138	.33	6.5	75	11.6	3.7	.2	8.8	2.8
12-inch rolok-bak (heavy duty)	Cement-lime	Mississippi	79, 80, 81	.44	7.7	124	16.1	2.8	1.2	13.4	4.0
		New England	139, 140, 141	.33	6.3	109	17.3	2.8	1.2	13.4	4.4
	Cement	Mississippi	82, 83, 84, 85, 86	.46	7.0	111	15.9	4.7	.2	10.9	3.5
		New England	142, 143, 144, 145, 146	.33	5.2	92	17.6	5.8	.3	13.5	4.0
12-inch rolok-bak (standard)	Cement	Mississippi	87	.50	5.6	80	14.3	5.5	.2	12.8	4.9
		New England	147	.28	4.9	73	14.8	5.2	.2	12.2	4.2
4-inch "economy"	Cement-lime	Mississippi	88, 89, 90	.42	8.5	65	7.6	2.1	.9	9.6	3.0
		New England	148, 149, 150	.29	7.3	60	8.2	2.1	.9	9.8	2.8
	Cement	Mississippi	91, 92, 93	.44	8.3	62	7.5	3.4	.1	8.0	2.8
		New England	151, 152, 153	.27	7.2	60	8.2	3.8	.2	9.0	2.6

(2) MATERIALS USED.—Table 3 also shows the amounts of the various mortar materials used for each square foot of wall surface. The amount of water used in the mortar is also reported. The number of bricks per square foot of wall surface was obtained by dividing the counted number of bricks in the wall by the area of the wall surface.

(3) COMPARATIVE CONSTRUCTION DATA FOR DIFFERENT TYPES OF WALLS.—In order to study the comparative construction data for different types of walls, only the walls built of Mississippi and New England brick will be considered, since no hollow walls were built of either the Chicago or the Detroit brick. In order to limit the variables still further, only walls of series 2 will be considered first. These walls were all built by one mason and included 60 walls each of Mississippi and New England brick. It should be remembered that the solid walls of this group had full horizontal and vertical mortar joints.

Although two different mortars were used, it is possible to bring them to a common basis for comparing the quantities of mortar materials by a study of the amounts of sand. This is permissible, since each mortar is essentially 1 part of cementing materials to 3 parts of sand.

Since the same number of walls was built of each kind of brick, the number of bricks per square foot of wall surface has been averaged for all the walls of one type and these values are given in Table 4 (A).

The rate of building will, of course, vary with the mason, the kind of structure, and other factors. The data given in Table 4 (A) were obtained with walls which were all of the same size, were built in the same laboratory and by the same mason and helper. A comparative study of building time can, therefore, be made from these data directly, although it should be remembered that there were no openings, jambs, or corners which might make some difference in the respective rates of building the different types of walls.

The 8-inch and the 12-inch solid walls have been used as the basis for a comparison of the materials and the time required for building the different types of walls. Since it seems more logical to compare the time required to build walls of equal size rather than the rate of building, the time ratios, which are proportional to the reciprocals of the rate of building, are also given. These ratios are plotted in Figure 14.

TABLE 4.—*Average construction data of solid and hollow walls of brick*

(A) WALLS OF SERIES 2

COMPARISON WITH 8-INCH SOLID WALLS

Type of walls	Number of walls	Sand	Brick per square foot	Rate of building	Ratios to solid walls: Sand	Ratios to solid walls: Brick	Ratios to solid walls: Rate of building	Ratios to solid walls: Time
		Lbs./ft.^{2}		*Sq.ft./hr.*				
8-inch solid	12	13.5	13.0	7.4	1.00	1.00	1.00	1.00
8-inch all-rolok	12	7.4	9.8	9.2	.55	.75	1.24	.81
8-inch A. r. F. b.[1]	12	7.4	9.7	9.6	.55	.75	1.30	.77
8-inch rolok-bak	12	8.6	11.1	8.0	.64	.86	1.08	.93
4-inch economy	12	9.1	7.9	7.8	.67	.61	1.05	.95

COMPARISON WITH 12-INCH SOLID WALLS

Type of walls	Number of walls	Sand	Brick per square foot	Rate of building	Ratios to solid walls: Sand	Ratios to solid walls: Brick	Ratios to solid walls: Rate of building	Ratios to solid walls: Time
12-inch solid	18	20.8	19.8	5.6	1.00	1.00	1.00	1.00
12-inch all-rolok	12	11.3	14.2	6.7	.54	.72	1.20	.83
12-inch A. r. F. b.[1]	12	10.9	15.3	6.6	.52	.77	1.18	.85
12-inch rolok-bak	18	12.6	16.5	6.3	.61	.83	1.12	.89

(B) WALLS OF SERIES 1

COMPARISON WITH 8-INCH SOLID WALLS

Type of walls	Number of walls	Sand	Brick per square foot	Rate of building	Ratios to solid walls: Sand	Ratios to solid walls: Brick	Ratios to solid walls: Rate of building	Ratios to solid walls: Time
8-inch solid	1	11.8	11.25	17.4	1.00	1.00	1.00	1.00
8-inch all-rolok	1	7.4	8.73	19.2	.63	.78	1.10	.91
8-inch A. r. F. b.[1]	1	12.2	8.90	17.5	1.03	.79	1.00	1.00
8-inch rolok-bak	1	8.8	10.00	20.5	.74	.89	1.18	.85

[1] All-rolok-in-Flemish-bond type of wall.

Tables 4 (A) and Figure 14 show that there is a considerable saving in brick and mortar materials in all the hollow walls as compared to solid walls of the same thickness. The all-rolok walls and the all-rolok walls in Flemish bond show a saving of at least 45 per cent in mortar materials and of about 25 per cent in the number of brick required. The rolok-bak walls, on the average, show savings of about 40 per cent in mortar materials and 15 per cent in brick. Of the eighteen 12-inch rolok-bak walls mentioned in Table 1, 16 were of the heavy-duty type and 2 of the standard type described in the reference. The time required to build the hollow walls is also less than for solid walls of equal thickness. Fewer brick are needed for the 4-inch "economy" walls than for the 8-inch hollow walls, but because of the back plastering the amount of mortar (per square foot of wall surface) was about the same as for the 8-inch hollow walls. On account of the time taken for plastering the back, the average amount of wall area built per hour was only 5 per cent more than with the solid 8-inch walls.

These walls, referred to in Table 4 (A) were built by a mason who was hired by the day, and they may be classed as construction under careful supervision. In order to have a comparison between this quality of work and work without careful supervision, the four walls (155 to 158) of series 1 may be considered. These were all 8-inch walls of series 1 built of Mississippi brick with cement mortar. The construction data for these walls are given in Table 4 (B).

(4) Thickness of the Mortar Joints.—The average thickness of the horizontal mortar joints is given in Table 3. These values

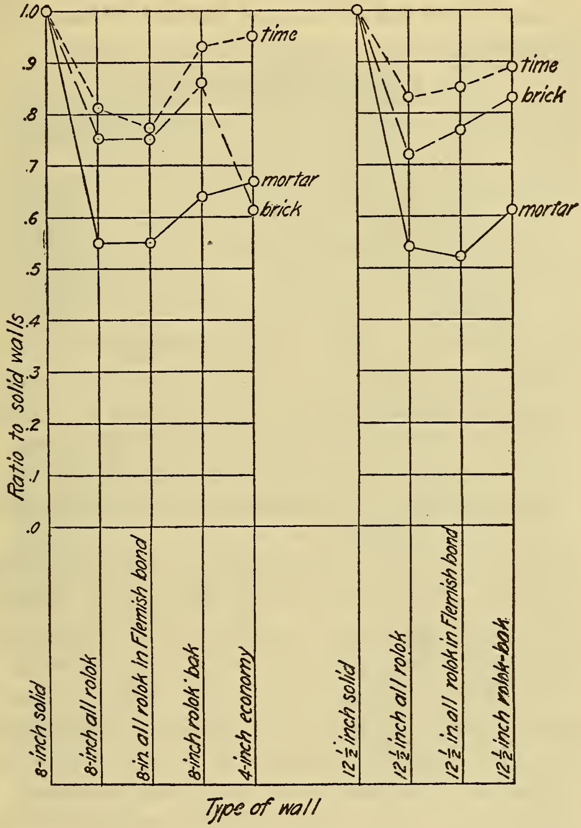

Figure 14.—*Comparative construction data of walls of series 2. The data from the 8-inch and 12-inch solid walls have been used as the basis of comparison*

were found by subtracting the total brick thickness (number of courses times average thickness of brick as given in Table 2) from the height of the wall and dividing by the number of mortar joints. The mortar joints in the walls of series 1 were much thicker than in those of series 2.

(f) AGING CONDITIONS

The walls remained in the laboratory, as shown in Figure 1, until they were tested.

(1) SCHEDULE OF BUILDING.—On account of the long time (more than one year) required for these tests, Table 5 is given to show the dates at which the walls were built and tested.

In order to minimize the effect of changes which might occur in curing conditions or change in workmanship, the walls 34 to 153 of Mississippi and New England brick, series 2, were built in the order shown by going down the columns of Table 1—that is, 34, 37, 40–91, 94–151, 35, 38, etc.

TABLE 5.—*Schedule of walls*

Series	Wall Nos.	Brick	Building started	Testing completed
1	1 to 17	Chicago	Apr. 4, 1926	June 21, 1926
2	19 to 33	Detroit	May 3, 1926	July 23, 1926
2	34 to 153	Mississippi and New England	May 27, 1926	Mar. 4, 1927
2	18	Chicago	July 31, 1926	Sept. 27, 1926
1	154 to 159	New England and Mississippi	Jan. 19, 1927	Mar. 22, 1927
2	160 to 167	Chicago	Aug. 19, 1927	Oct. 29, 1927
2	168	do	Sept. 1, 1927	Feb. 16, 1928

(2) THE LABORATORY.—The curing conditions in the laboratory, shown in Figure 1, in which all the walls were built and tested, was generally about the same as out of doors during the spring, summer, and autumn, since large doors were nearly always open. During the colder part of the year it was heated. Being indoors, the walls were, of course, protected from precipitation and from the direct rays of the sun.

(3) DAMP-CURED WALLS.—In order to determine whether brick walls, built with cement mortar, kept damp for several days after construction are stronger than similar walls allowed to age under normal conditions in the laboratory, the walls listed in Table 1 as "wetted" were built. These walls, which were all laid in cement mortar, were covered with burlap, as shown in Figure 15, as soon as they had been completed. The burlap was kept wet for one week after the walls had been built and was then removed. These wet walls were similar as to the kind of brick, mortar, workmanship, and size to an equal number of walls which were not covered with wet burlap, as may be seen in Table 1.

(g) AGE

The walls were tested from 57 to 62 days after construction, with the exception of wall 168, built of Chicago brick with cement mortar, which was tested when 169 days old for the purpose of exhibiting the test to a group of visitors.

(h) TESTING MACHINE

The walls were tested in the 10,000,000-pound capacity compression machine, shown in Figures 1 and 16. This machine is of the vertical type and is capable of testing specimens whose height does not exceed 25 feet and whose width in the clear does not exceed 6 feet.

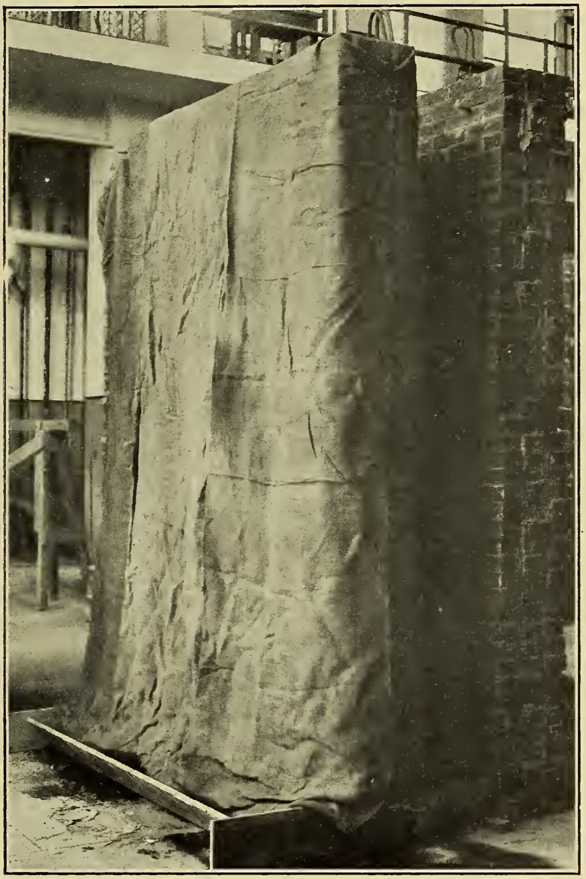

Figure 15.—*A wall covered with burlap for damp curing*

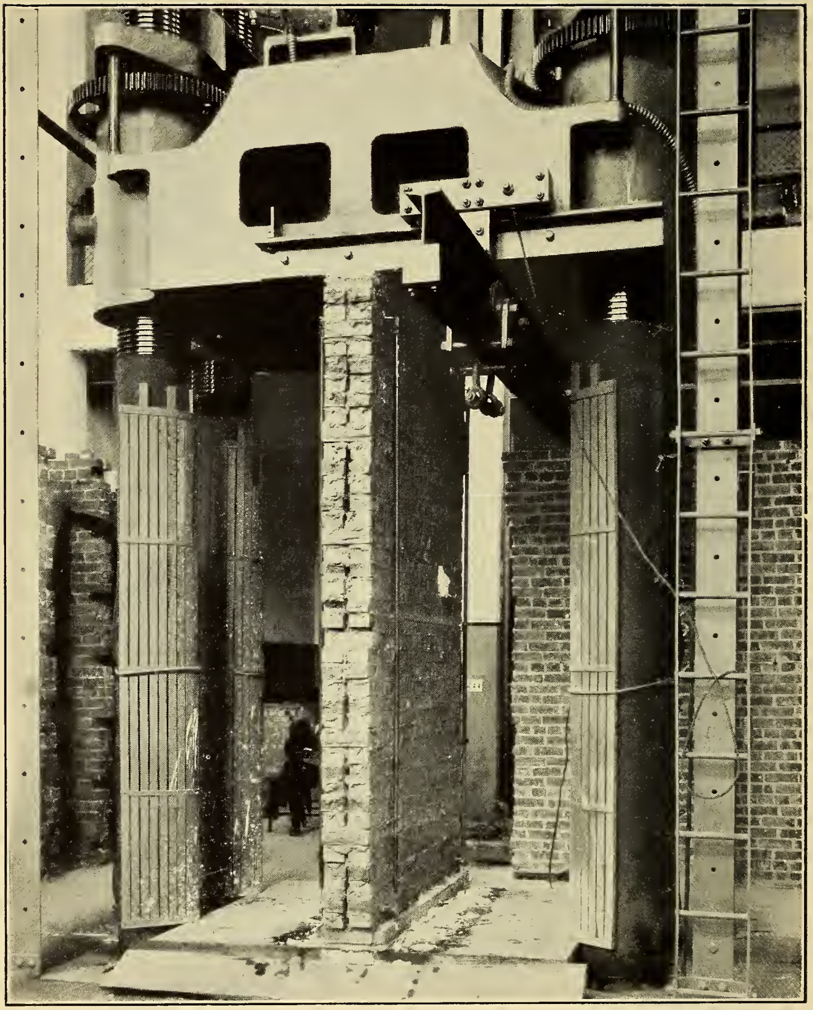

Figure 16.—*A wall in the 10,000,000-pound capacity testing machine ready for test*

The upper head during a test remains stationary, but for the purpose of adjusting the machine to the height of the specimen this head is moved by large nuts turning on the four 13½-inch diameter screws of the machine. These nuts are turned by a gearing mechanism which is driven by an electric motor placed on the head.

The lower platen, 6 feet square, rests on a spherical base of 5 feet radius which is mounted upon a vertically acting piston of 50 inches diameter and 24-inch stroke. There is attached to the bottom of this ram a guiding plunger 14 inches in diameter and 2 feet 5 inches long which fits into the large base casting of the testing machine and serves for proper centering of the parts.

The lower, or straining platen, is subject to the oil pressure in the cylinder, which, at the capacity of the machine, is approximately 5,000 lbs./in.^{2} The oil pressure communicates through auxiliary piping with a smaller piston of 5$\frac{9}{16}$ inches diameter. This piston has a "knife-edge" bearing on the main lever, *M*, of the testing machine lever system. (See fig. 17 for reference to the various parts by letters.) The ratio of the areas of the large and small piston is approximately as 80:1, the weighing lever, *L*, being graduated up to 2,000,000 pounds to read the actual load on the specimen. For loads greater than 2,000,000 pounds four weights, *W*, are provided, which may be placed on the end of the lever as desired. Each of these weights when attached to the end of the lever has a moment about the balance point *B* of the lever equal to that of the poise when it is at the 2,000,000-pound graduation, *2 M*. Thus, if one weight is used and the poise, *P*, indicates a given load, the force on the specimen is equal to 2,000,000 pounds plus the poise reading.

The pressure in the cylinder of the machine is obtained by means of a triple plunger oil pump, *O*, having an air dome, *A*, for equalizing the pulsations of the three pistons. The pump is belt driven by an electric motor, *E*. The piping from the pump leads to the bottom of the cylinder and is directed downward toward its base, while the piping which leads to the weighing piston is taken from the top of the cylinder, as far as possible from the other pipe, and where there is the least disturbance.

The passage of oil from the pump is controlled by two valves, *V*, and the system is protected from dangerous pressures by an automatic overload relief valve. The oil can also be passed directly from the pump back to the reservoir by means of a hand-controlled relief valve, *R*. The speed of the lower platen may be varied in the following manners: By varying the lengths of stroke of the pump pistons through the handwheel, *H;* by operating a by-pass needle valve, *N*, which controls the size of the passage in the valve block; by manipulating the globe valves, *V*, or the relief valve, *R;* or by varying the operating speed of the motor through the motor-controller switch.

The speed of the main piston may in this manner be varied from zero to ⅝ inch per minute at no load.

(i) METHOD OF TESTING

The walls were tested in compression under central loading. For these tests the channel at the base of the wall was bedded in plaster of Paris. The lower platen was then tilted, if necessary, until the wall was plumb and the top of the wall was nearly parallel to the lower surface of the upper head of the testing machine. A cap of plaster of Paris (calcined gypsum) was then spread on the top of the wall and the upper head lowered until the space between it and the wall was filled with plaster. The gypsum was allowed to set for at least an hour before the test was begun.

Vertical compressometers having a gage length of about 100 inches were attached near each corner, as shown in Figure 16. Horizontal extensometers were also fastened along the length on each side at mid height of the wall. These had a gage length of about 48 inches. The dial micrometers were graduated to 0.001 inch, and readings were taken at each 50 or 100 lbs./in.^{2} increment of load on the wall. The vertical speed of the lower platen was about 0.06 inch per minute during the application of load. When readings were being taken, the load was held constant.

4. WALLETTES

One hundred and twenty-nine wallettes or small walls, each about 18 inches long and 34 inches high, were built, which differed only in size from the wall of the same number. The walls and wallettes of the same number corresponded as to brick, mortar, type, curing conditions, and workmanship. No wallettes of the "economy" type were built, since that design is not adapted for specimens of wallette size. A group of wallettes is shown in Figure 18. The wallettes were built to determine whether walls smaller than the 6 by 9 foot specimens possessed compressive strengths which had a definite relation to those of the wall specimens. All but the strongest wallettes were tested in a 600,000-pound capacity universal testing machine using a spherical bearing, as shown in Figure 19. One of the wallettes (No. 104) tested in the 600,000-pound capacity machine could not be broken. It was then retested in the 10,000,000-pound machine. All other wallettes of this type which were tested later were then tested in the 10,000,000-pound machine.

IV. RESULTS OF THE TESTS WITH DISCUSSION

1. BRICK

The results of the tests of the single bricks are given in Table 6. Each average value, except those for shearing strength, is the average result from 50 tests.

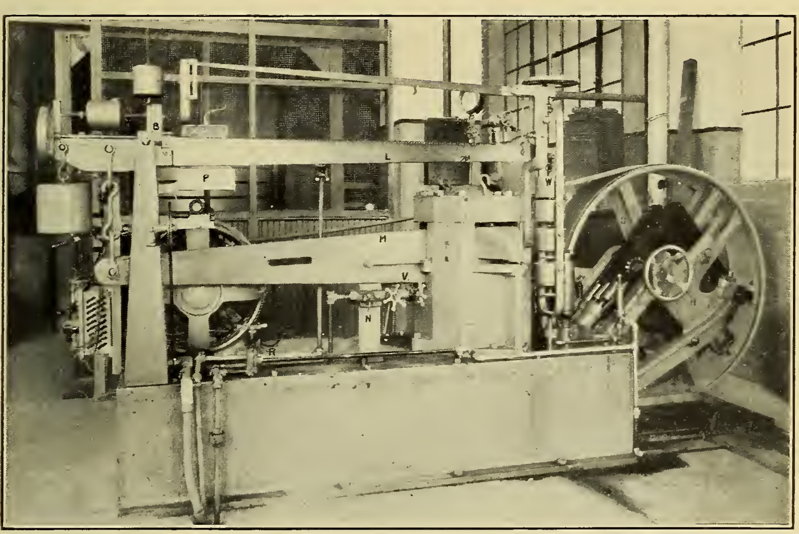

FIGURE 17.—*Pump and weighing mechanism of the 10,000,000-pound capacity testing machine*

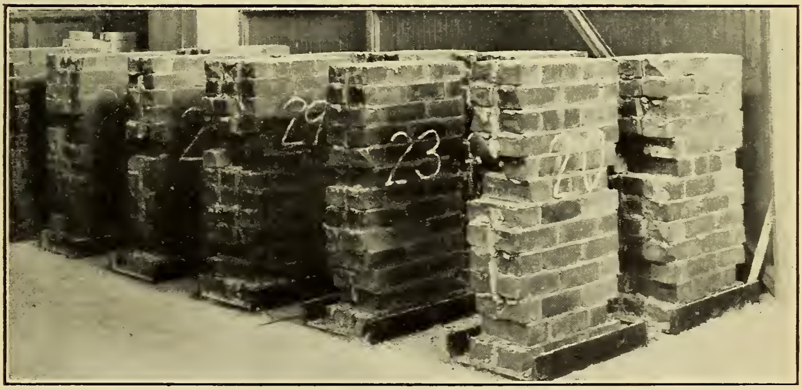

FIGURE 18.—*A group of wallettes of series 2, built of Detroit brick*

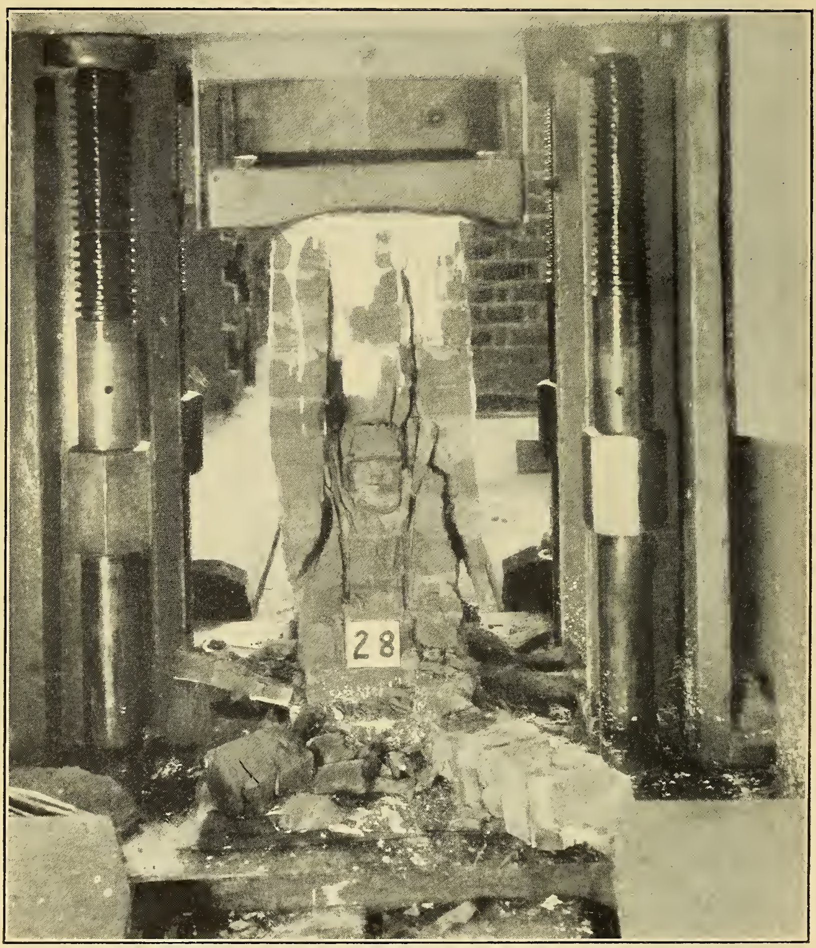

FIGURE 19.—*A wallette in the 600,000-pound capacity testing machine*

Wallette 28, of series 2, built of Detroit brick, laid in cement mortar. The maximum stress withstood by this specimen was 1,605 lbs./in.^{2}.

TABLE 6.—*Physical properties of the brick*

Kind of brick	Value	Absorption		Modulus of rupture			Compressive strength						Tensile strength	Shearing strength
							Flatwise			Edgewise				
		5-hour boiling	48-hour immersion	Flatwise	Flatwise (wet)	Edgewise	Whole brick (dry)	Half brick (dry)	Half brick (wet)	Whole brick (dry)	Half brick (dry)	Half brick (wet)		
		Per cent	*Per cent*	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}
Chicago	Maximum	23. 0	22. 0	2, 420	2, 830	2, 990	4, 820	4, 720	6, 120	6, 660	5, 860	6, 070	750	1, 445
	Minimum	10. 5	4. 9	520	380	420	2, 190	2, 140	2, 430	1, 330	1, 640	2, 410	204	940
	Average	16. 5	11. 7	1, 225	1, 470	1, 340	3, 460	3, 280	3, 670	2, 810	3, 350	3, 620	417	[1] 1, 100
Detroit	Maximum	25. 5	22. 5	1, 062	972	1, 055	4, 850	5, 950	4, 320	4, 360	4, 230	6, 560	332	1, 500
	Minimum	19. 4	16. 4	422	327	226	2, 270	2, 110	1, 740	2, 690	2, 410	1, 680	123	810
	Average	22. 3	20. 7	670	632	680	3, 255	3, 540	2, 520	3, 380	3, 270	3, 165	222	[1] 1, 165
Mississippi	Maximum	25. 1	21. 8	1, 540	1, 390	1, 480	6, 460	6, 510	7, 100	5, 760	7, 330	5, 630	513	2, 190
	Minimum	18. 4	12. 3	324	441	387	2, 590	2, 390	1, 740	1, 460	2, 320	2, 160	148	1, 155
	Average	21. 7	16. 7	820	750	760	3, 625	3, 410	3, 520	3, 200	3, 625	3, 620	317	[1] 1, 590
New England	Maximum	14. 9	11. 9	2, 330	3, 540	2, 340	14, 160	12, 270	11, 830	16, 400	15, 500	18, 750	1, 160	4, 255
	Minimum	3. 1	2. 4	940	818	448	5, 180	5, 380	3, 710	5, 380	6, 390	5, 510	325	2, 460
	Average	9. 2	6. 9	1, 550	1, 400	1, 640	9, 420	8, 600	6, 990	10, 300	11, 470	11, 020	601	[2] 3, 550

[1] Average of 10 tests on half brick.

[2] Average of 4 tests on 1-inch thick cut slab.

The number 50 represents a complete sampling of the shipment. While most determinations were checked by two or more independent samplings and tests, for the purposes of this paper a particular set of samples was selected and the others disregarded. On the basis of the large number of tests made, it can be stated that the strengths of a given lot as determined by averages of 50 specimens may differ by as much as 10 per cent. Hence, small differences, such as appear between the wet and dry compressive and transverse strengths of the Chicago brick, for example, should be disregarded, being within the variations due to sampling alone.

While, in general, there is a fair correlation between the different measures of strength, comparing one kind of brick with another, certain divergencies are evident which may well have an important effect on masonry strength. This will be discussed later in the paper. For the present, attention is called to Table 7, where the ratios of these various physical properties are given.

Disregarding comparisons of strength wet with strength dry, and considering the mean deviation divided by the mean as given in Table 7 as a measure of agreement, the most constant ratios are those of tensile strength to modulus of rupture. The ratio of modulus of rupture to shearing strength shows the greatest deviation.

Table 7.—*Ratios of various physical properties of brick*

Kind of brick	Absorption	Compressive stength of half brick		Modulus of rupture (flat, dry)	Tensile strength	Modulus of rupture (flat, wet)	Modulus of rupture (flat, dry)	Tensile strength	Shearing strength
	48-hour cold	Edge, dry	Flat, wet	Compressive strength of half (flat, dry)	Modulus of rupture (flat, dry)	Modulus of rupture (flat, dry)	Shearing strength	Compressive strength of half (flat, dry)	Compressive strength of half (flat, dry)
	5-hour boiled	Flat, dry	Flat, dry						
1	2	3	4	5	6	7	8	9	10
Chicago	0.71	1.02	1.12	0.37	0.34	1.20	1.11	0.13	0.34
Detroit	.93	.92	.71	.19	.33	.94	.58	.06	.33
Mississippi	.77	1.06	1.03	.24	.39	.92	.52	.09	.47
New England	.75	1.33	.81	.18	.39	.90	.44	.07	.41
Mean deviation / Mean	.08	.11	.17	.24	.08	.10	.34	.22	.14

A study of Tables 6 and 7 will show that the Chicago brick is different from the other three kinds in that its ratio of modulus of rupture and of tensile strength to compressive strength and to shearing strength is markedly higher than are the corresponding strength ratios for the other three bricks, as may be noted in columns 5, 8, and 9 of Table 7. This is possibly explained by the structure of the brick, end cut and laminated, which gives the effect of a bundle of fibers running lengthwise of the brick.

Of the other three kinds of brick, two represent the soft-mud and one the dry-press method of manufacture.

In the original plan for these tests it was the intention to use bricks corresponding to the four grades in the American Society for Testing Materials' Specification for Building Brick (C21–24). On the basis of the average values here given these brick would classify as follows:

	Absorption, 5-hours boiling	Modulus of rupture flatwise	Compressive strength halves on edge
Chicago	Medium	Vitrified	Medium.
Detroit	Soft	Hard	Do.
Mississippi	do	do	Hard.
New England	Hard	Vitrified	Vitrified.

Under the American Society for Testing Materials new Tentative Specification for Building Brick (made from clay or shale) (C62–28T) these brick classify as follows:

	Compressive strength halves flatwise	Modulus of rupture flatwise
Chicago	B	A
Detroit	B	A
Mississippi	B	A
New England	A	A

For both these classifications it is provided that the grading "shall be determined by the results of the tests for that requirement in which it is lowest unless otherwise specified * * *."

Figures 20, 21, 22, and 23 give the distribution of the individual tests, averages of which are given in Table 6. The 50 tests in each group are not enough to give a satisfactory distribution, but these graphs give an idea of the variability of the brick.

2. MORTAR

The average results of the tests of the mortar specimens are given in Table 8.

TABLE 8.—*Compressive strength of mortar specimens*

[Cylinders 2 inches in diameter, 4 inches long]

REPRESENTING WALLS 1 TO 18 AND 160 TO 162

Mortar	Proportions (by volume)	Strength	
		Cured wet	Cured dry
		Lbs./in.^{2}	*Lbs./in.*^{2}
Lime	1¼ L: 3S	--------	90
Cement-lime	1 C: 1¼ L: 6S	1,070	500
Cement	1 C: 3S	3,580	1,460

REPRESENTING WALLS 19 TO 159 AND 163 TO 168

Cement-lime	1 C: 1 L: 6S	1,100	750
Cement	1 C: $\frac{1}{10}$ L: 3S	3,260	1,950

3. WALLS

(a) BASIS OF COMPUTATIONS

The sectional area of the wall was obtained by multiplying the average thickness by the length (72 inches). All wall stresses, except some of those in Table 10, were obtained by dividing the load by this measured (not nominal) gross area. The stresses in the hollow walls are also based on the gross measured areas.

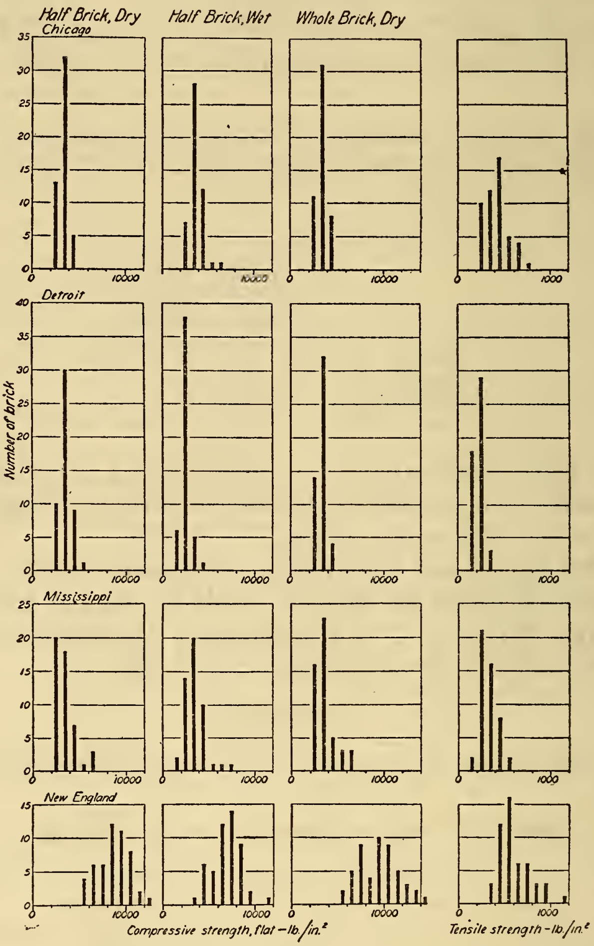

FIGURE 20.—*Results of the tests on brick*

Compressive strength, flat, half brick, half brick dry, half brick wet, and whole brick dry, and tensile strength

(b) DEFORMATION OF THE WALLS

(1) STRESS-STRAIN CURVES.—The average stress-strain curves of the solid walls of series 1 built of Chicago brick are shown in Figure 24. These curves show the differences in stiffness due to differences in the mortar. Both the average vertical compression and the horizontal extension of the wall at mid height have been plotted against the com-

pressive stress. The horizontal extension is much less than the vertical compression, but no constant relation between them, such as the nearly constant Poisson's ratio for some metals, appears to exist. The ratio of extension to compression, however, increases with increase in stress.

The relative stiffness of the different types of walls is shown in Figure 25. This shows average stress-strain curves for the 8-inch walls of series 2 of Mississippi brick laid in cement mortar. These curves for the different types of walls are typical of those found in the other groups of walls. The solid walls deform less than the hollow walls and the different types of hollow walls appear to deform about equally for equal stresses.

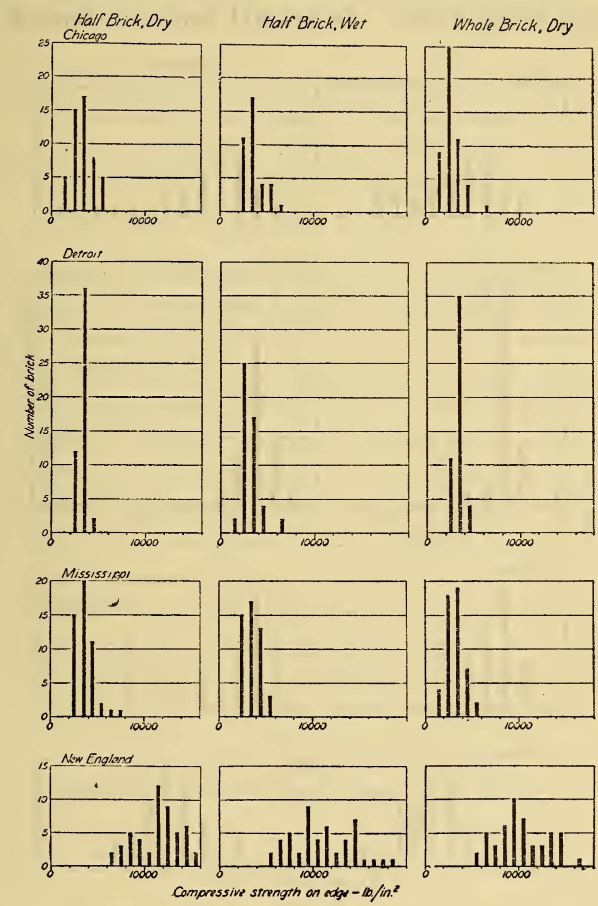

FIGURE 21.—*Results of the tests on brick*

Compressive strength on edge, half brick dry, half brick wet, and whole brick dry

Average stress-compression curves for 12-inch solid walls of series 2 built with cement mortar and of different kinds of brick are shown in

Figure 26. Since the same mortar mixture was used for all of these walls the differences in stiffness are due in large part to differences in the properties of the brick, although differences in the thickness of the mortar joints doubtless had an influence.

(2) SECANT MODULUS OF ELASTICITY.—For the walls laid in cement-lime and cement mortars the stress-strain curves are, for low stresses, approximately straight lines. In general, however, there is no value for a modulus of elasticity which is constant over a large stress range. For computing the shortening of a wall under the first application of working loads, the secant modulus of elasticity, obtained by dividing the stress by the corresponding value of the compressive strain, may be of use. These values are given in Table 9. The stress ranges are—

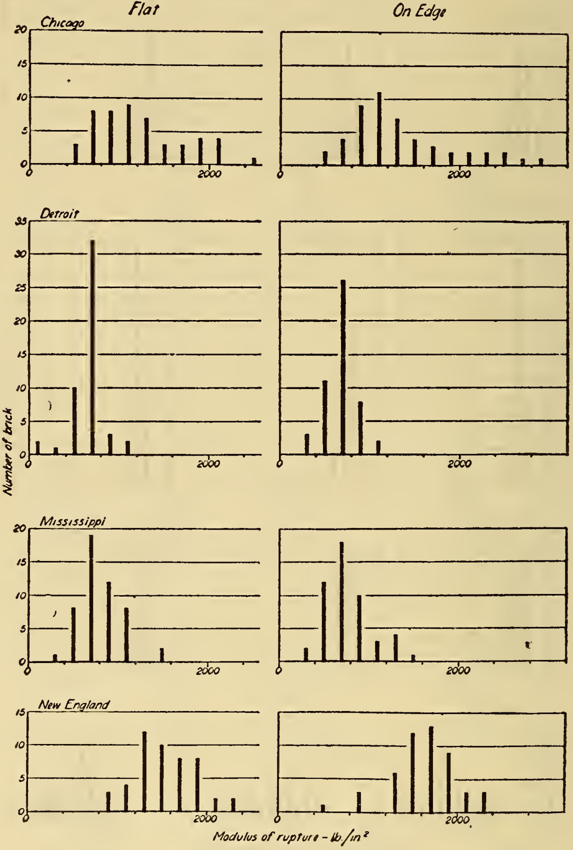

FIGURE 22.—*Results of tests on brick*

Modulus of rupture, flat and on edge

0 to 125 lbs./in.^{2} for lime mortar,
0 to 200 lbs./in.^{2} for cement-lime mortar, and
0 to 250 lbs./in.^{2} for cement mortar.

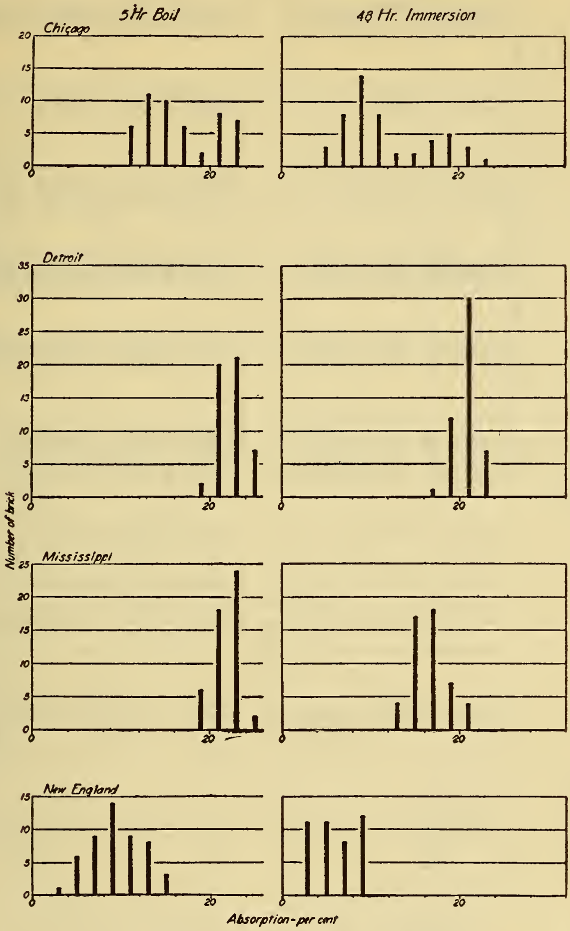

FIGURE 23.—*Results of tests on bricks*

Absorption per cent, 5-hour boil and 48-hour cold immersion

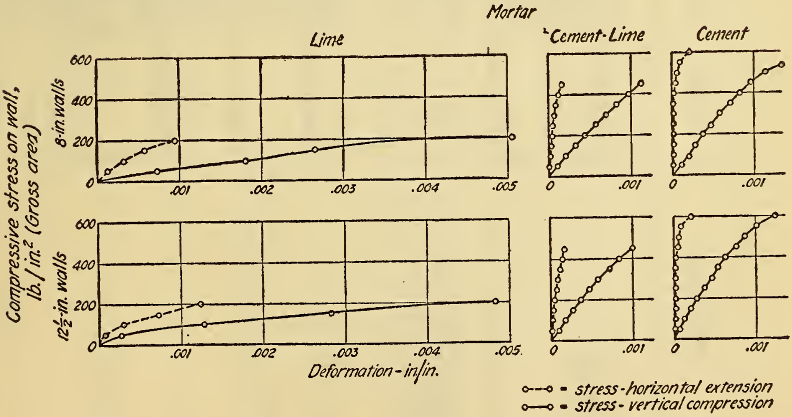

FIGURE 24.—*The average stress-strain curves of the solid walls of series 1 built of Chicago brick*

TABLE 9.—*Results of compressive tests of brick walls*

(A) WALLS OF SERIES 1

Type of wall	Mortar	Kind of brick	Workmanship (type of bed joints)	Curing conditions	Wall Nos.			Average secant modulus of elasticity	Average stress at first crack	Wall strength			
					a	b	c			a	b	c	Average
								Lbs./in.^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}
8-inch solid	Lime	Chicago	Furrowed	Ordinary	1	2	3	54, 000	200	255	250	315	275
	Cement-lime	do	do	do	7	8	9	459, 000	520	575	620	590	595
	Cement	do	do	do	13	14	15	554, 000	640	660	750	580	665
		Mississippi	do	do	155			493, 000	870	870			870
		do	Spread	do	159			974, 000	1, 480	1, 480			1, 480
		New England	Furrowed	do	154			2, 040, 000	1, 500	2, 030			2, 030
12-inch solid	Lime	Chicago	do	do	4	5	6	69, 600	210	295	350	250	300
	Cement-lime	do	do	do	10	11	12	556, 000	510	580	575	580	580
	Cement	do	do	do	16	17		686, 000	600	655	655		655
8-inch all-rolok	do	Mississippi	do	do	156			379, 000	335	440			440
8-inch all-rolok in Flemish bond	do	do	do	do	157			509, 000	270	535			535
8-inch rolok-bak	do	do	do	do	158			453, 000	485	745			745

(B) WALLS OF SERIES 2

Type of wall	Mortar	Kind of brick	Workmanship (type of bed joints)	Curing conditions	Wall Nos. a	Wall Nos. b	Wall Nos. c	Average secant modulus of elasticity	Average stress at first crack	Wall strength a	Wall strength b	Wall strength c	Wall strength Average
8-inch solid	Cement-lime	Detroit	Spread	Ordinary	19	20	21	638, 000	515	1, 060	905	760	910
		Mississippi	do	do	34	35	36	1, 031, 000	1, 125	965	1, 175	1, 340	1, 160
		New England	do	do	94	95	96	2, 049, 000	1, 165	1, 785	1, 875	1, 710	1, 790
	Cement	Chicago	do	do	160	161	162	1, 041, 000	865	800	870	965	880
		do	do	do	163	164	165	1, 014, 000	830	885	925	755	855
		Detroit	do	do	22	23	24	727, 000	790	1, 305	895	1, 050	1, 080
		do	do	Wetted	33			767, 000	610	1, 055			1, 055
		Mississippi	do	Ordinary	37	38	39	1, 300, 000	1, 270	1, 335	1, 405	1, 405	1, 380
		New England	do	do	97	98	99	2, 360, 000	1, 750	2, 040	2, 950	2, 915	2, 635
12-inch solid	Cement-lime	Detroit	do	do	25	26	27	727, 000	590	1, 050	940	965	985
		Mississippi	do	do	40	41	42	1, 288, 000	1, 155	1, 375	1, 305	1, 225	1, 300
		New England	do	do	100	101	102	2, 461, 000	1, 100	1, 815	1, 990	1, 855	1, 890
	Cement	Chicago	Shoved	do	18			1, 350, 000	1, 165	1, 165			1, 165
		do	Spread	do	166	167		1, 060, 000	875	890	1, 080		985
		do	do	169 days old	168				1, 065	1, 200			1, 200
		Detroit	do	Ordinary	28	29	30	935, 000	800	1, 165	1, 345	1, 115	1, 210
		do	do	Wetted	31	32		809, 000	665	1, 040	1, 165		1, 105
		Mississippi	do	Ordinary	43	44	45	1, 538, 000	1, 390	1, 710	1, 855	1, 350	1, 640
		do	do	Wetted	46	47		1, 945, 000	1, 380	1, 305	1, 875		1, 590
		do	Shoved	Ordinary	48			1, 082, 000	1, 200	1, 465			1, 465
		New England	Spread	do	103	104	105	2, 652, 000	2, 310	2, 440	3, 230	2, 695	2, 790
		do	do	Wetted	106	107		2, 455, 000	1, 750	1, 750	3, 270		2, 510
		do	Shoved	Ordinary	108			2, 024, 000	2, 530	2, 720			2, 720

8-inch all-rolok	Cement-lime	Mississippi	Spread	do	49	50	51	709, 000	600	745	655	890	765
		New England	do	do	109	110	111	1, 103, 000	415	1, 055	780	795	875
	Cement	Mississippi	do	do	52	53	54	883, 000	785	850	735	1, 175	920
		New England	do	do	112	113	114	1, 209, 000	430	1, 005	1, 065	795	955
12-inch all-rolok	Cement-lime	Mississippi	do	do	55	56	57	687, 000	565	645	725	750	705
		New England	do	do	115	116	117	1, 105, 000	450	805	785	640	740
	Cement	Mississippi	do	do	58	59	60	681, 000	665	795	745	870	800
		New England	do	do	118	119	120	1, 217, 000	665	775	935	895	870
8-inch all-rolok in Flemish bond	Cement-lime	Mississippi	do	do	61	62	63	743, 000	545	800	750	695	750
		New England	do	do	121	122	123	1, 199, 000	600	555	745	610	640
	Cement	Mississippi	do	do	64	65	66	738, 000	530	825	720	855	800
		New England	do	do	124	125	126	1, 712, 000	630	680	925	720	775
12-inch all-rolok in Flemish bond	Cement-lime	Mississippi	do	do	67	68	69	739, 000	485	570	640	810	675
		New England	do	do	127	128	129	1, 108, 000	575	890	900	700	830
	Cement	Mississippi	do	do	70	71	72	804, 000	500	550	660	920	710
		New England	do	do	130	131	132	1, 422, 000	605	940	1, 005	880	940
8-inch rolok-bak	Cement-lime	Mississippi	do	do	73	74	75	857, 000	810	950	905	965	940
		New England	do	do	133	134	135	1, 151, 000	530	815	1, 155	680	880
	Cement	Mississippi	do	do	76	77	78	859, 000	905	925	890	950	920
		New England	do	do	136	137	138	2, 074, 000	910	1, 270	1, 245	1, 105	1, 205
12-inch rolok-bak (heavy-duty)	Cement-lime	Mississippi	do	do	79	80	81	833, 000	515	775	830	950	850
		New England	do	do	139	140	141	1, 316, 000	600	1, 150	830	910	965
	Cement	Mississippi	do	do	82	83	84	782, 000	755	1, 035	835	955	940
		do	do	Wetted	85	86		866, 000	650	1, 025	905		965
		New England	do	Ordinary	142	143	144	1, 694, 000	775	1, 635	1, 525	1, 610	1, 590
		do	do	Wetted	145	146		1, 803, 000	740	1, 400	1, 250		1, 325
12-inch rolok-bak (standard)	Cement	Mississippi	do	Ordinary	87			749, 000	985	1, 010			1, 010
		New England	do	do	147			1, 633, 000	450	1, 160			1, 160
4-inch "Economy"	Cement-lime	Mississippi	do	do	88	89	90	1, 155, 000	1, 375	1, 370	1, 365	1, 565	1, 435
		New England	do	do	148	149	150	1, 826, 000	1, 235	1, 960	1, 975	1, 880	1, 940
	Cement	Mississippi	do	do	91	92	93	1, 257, 000	1, 575	1, 650	1, 350	1, 875	1, 625
		New England	do	do	151	152	153	2, 460, 000	2, 275	2, 755	3, 520	3, 160	3, 145

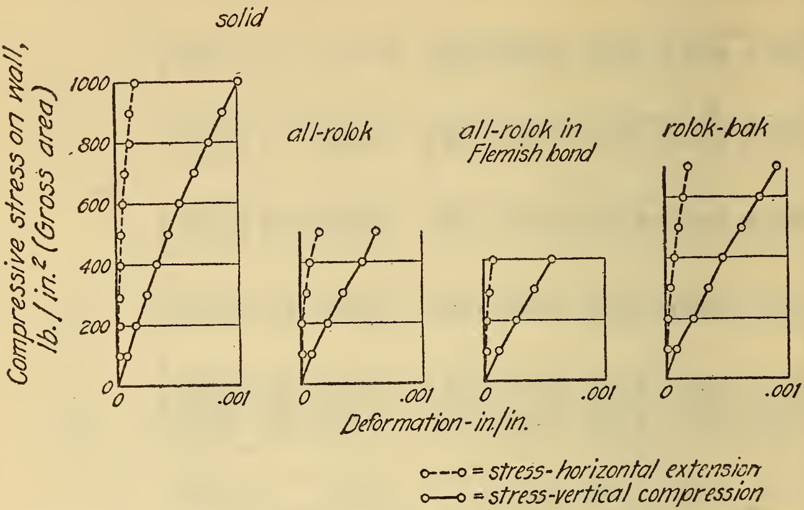

FIGURE 25.—*The average stress-strain curves for different types of 8-inch walls of series 2*

The walls were built of Mississippi brick laid in cement mortar

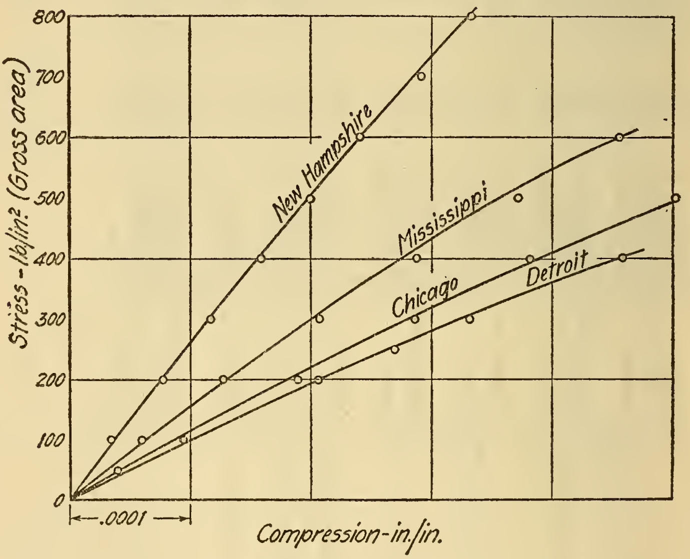

FIGURE 26.—*Average stress-compression curves for walls built of different kinds of brick*

The walls were 12-inch solid walls of series 2 laid in cement mortar

(3) Permanent Set.—The elastic behavior of these brick walls was found to be similar to that found for the masonry piers tested at Columbia University.[7] Upon release of load, a permanent set was found, and upon reapplication of the load, if the former load was not exceeded, the vertical deformation in the wall measured from its initial condition was only a little more than it was at the initial application of the load. Figure 27 shows the stress-compression curves for wall 42 which was subjected to repeated loadings. The slopes of the lines, which represent an increase of load, gradually decrease as higher loads are applied, although for the smaller stresses there is very little difference in the modulus of elasticity for consecutive loads. The deformation found on again attaining a certain load after a load release is slightly greater than the initial deformation, but upon proceeding to a higher load, the compression at that load appears to be equal to what it would have been if no release had taken place. In other words, the envelope of the stress-compression relations represented by the dotted line of Figure 27 with repeated loading appears to represent approximately the primitive stress-compression properties of the wall.

One wall in each group of three was subjected to a release of load test. Compressometer readings were taken as the load increased until the stress was reached for which the secant modulus of elasticity was computed. The stress was then reduced to 50 lbs/in.^{2}, readings were taken, and the load was reapplied. These second-loading moduli were in all cases larger than the corresponding values of the secant modulus of elasticity. For the lime-mortar walls the second loading moduli were more than three times as great as the primitive secant moduli, while with the other mortars the increase was from 10 to 50 per cent. Upon the release of load from a higher stress to 50 lbs./in.^{2}, a permanent set was always found. A typical stress-set curve is shown in Figure 27. The ordinates represent the stress from which release took place and the abscissas, the compression set at 50 lbs./in.^{2}, the stress to which the load was reduced. These set curves are fairly straight for the lower stresses, but for higher stresses the set increases more rapidly than the load.

(c) BEHAVIOR OF THE WALLS UNDER LOAD

In the solid lime-mortar walls (walls 1 to 6), as the load was increased the mortar was crushed and squeezed out of the horizontal beds. Soon after this occurred stretchers and headers broke, and at the maximum load more of the headers were broken and cracks appeared in many of the stretchers. These walls were all built of the end-cut Chicago brick and many of the stretchers split longitudinally.

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[7] A. H. Beyer and W. J. Krefeld, Comparative Tests of Clay, Sand-Lime, and Concrete Brick Masonry, Bulletin No. 2, Department of Civil Engineering, Columbia University; 1923.

In the solid walls built with the cement-lime and the cement mortars longitudinal failure of the stretchers predominated in the walls

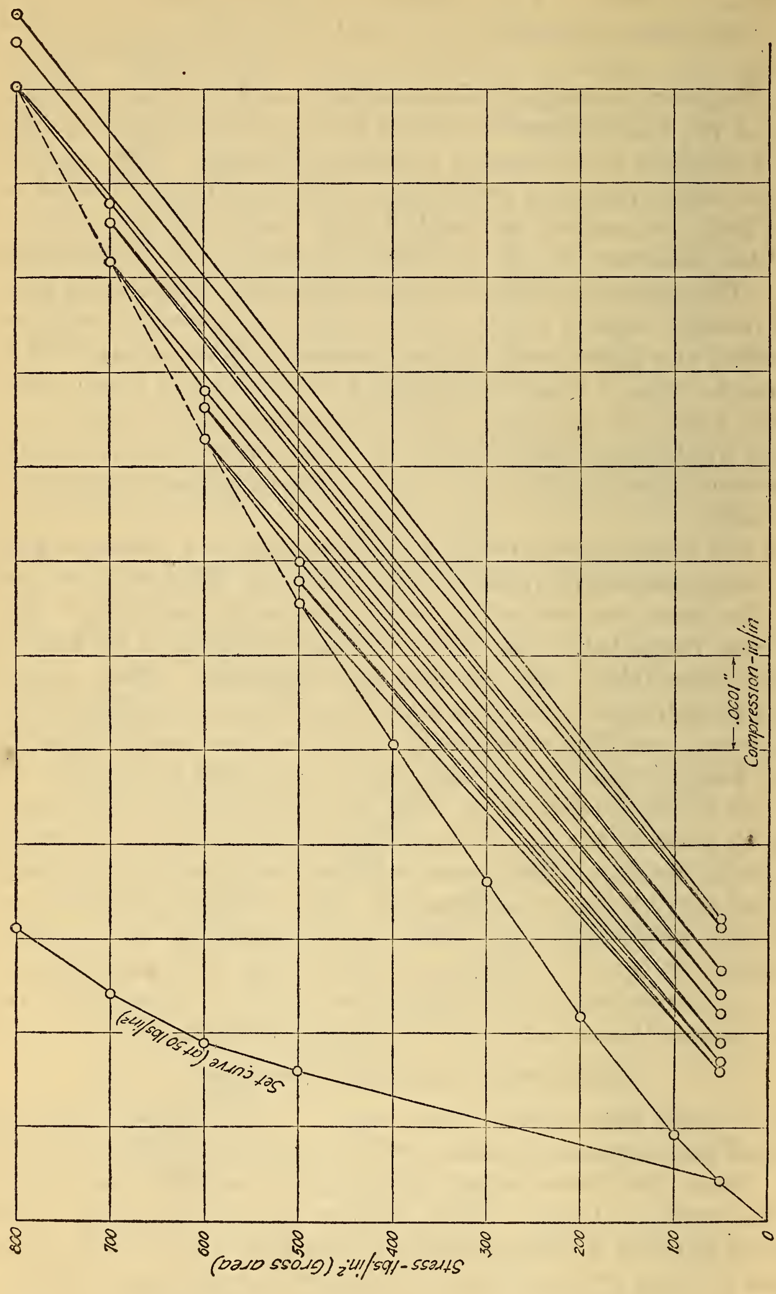


FIGURE 27.—*Stress compression and set curves for wall 42, a 12-inch solid wall of series 2, built of Mississippi brick, laid in cement-lime mortar*

of Chicago brick, while with the other kinds of brick, all of which were molded, the failure of the headers was characteristic. At the

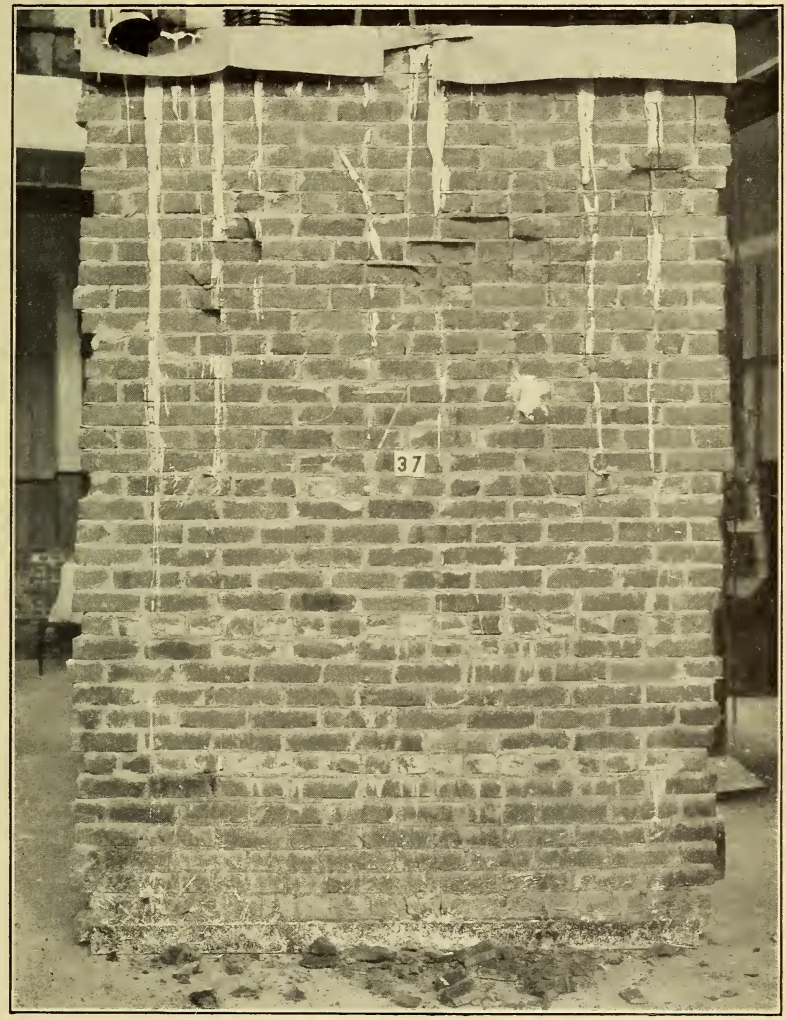


FIGURE 28.—*The 8-inch solid wall 37 of series 2, built of Mississippi brick, laid in cement mortar, after test*

The strength of this wall was 1,335 lbs./in.^{2}.

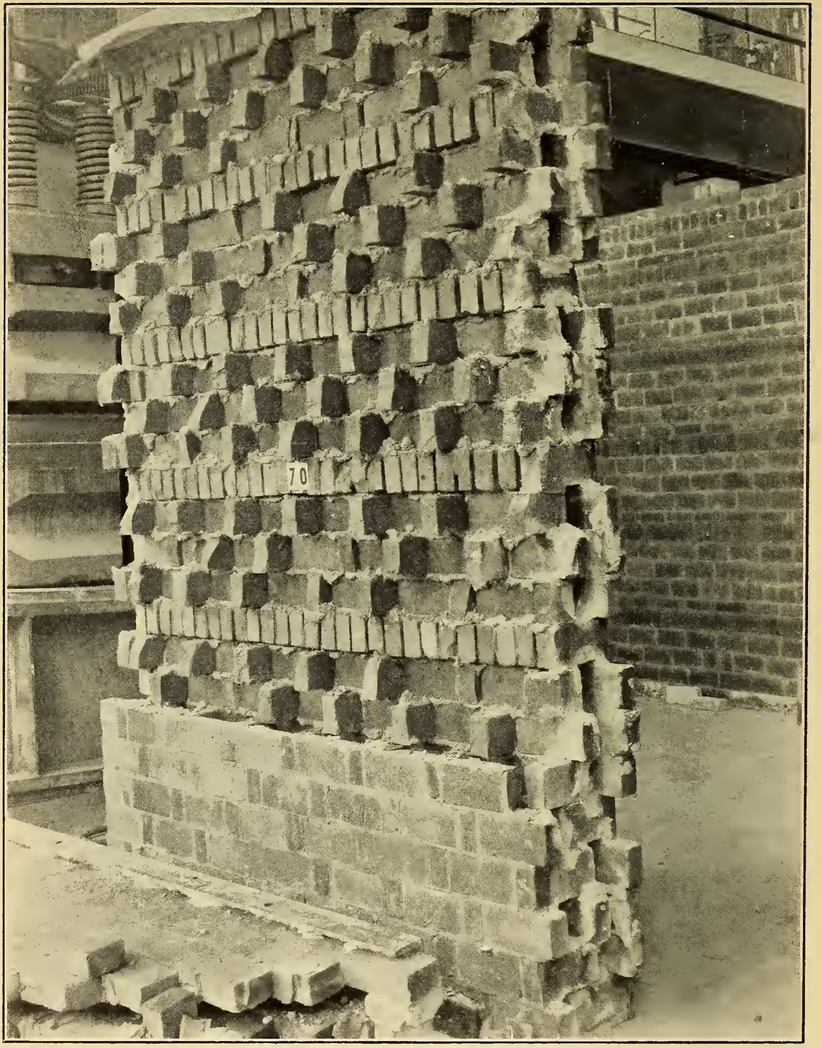


FIGURE 29.—*The 12-inch all-rolok in Flemish bond wall 70 of series 2, built of Mississippi brick, laid in cement mortar, after test*

The strength of this wall was 550 lbs./in.^{2}.

maximum load nearly all headers and many stretchers had broken, and in some cases, especially with the cement mortar, spalling of the brick and vertical cracks also occurred, as shown in Figure 28. No crushing of the mortar was observed except with the lime mortar.

The failure of the hollow walls was characterized by broken headers. Many of the 8-inch walls of the all-rolok and the all-rolok in Flemish bond types continued to take load until all the headers had been broken and total collapse took place. In the 12-inch walls of these types the rear withes often fell, as may be seen in Figure 29.

The failure of the rolok-bak walls was also characterized by header failures and the collapse of the rear rowlock withe.

In the "economy" walls the headers broke first, then the mortar plastering loosened, and finally stretcher cracks appeared. At the maximum load only the 4-inch withe was withstanding the load. The area of the pilasters has, however, been included in the area of the walls used to calculate the maximum stress.

The average values for the stresses when the first crack was seen are given in Table 9. There seems to be no definite relation between these stresses and the maximum stresses that the walls withstood, although there was, of course, a tendency for the load at failure to be larger if the load at first crack was large.

The loading was not continued after a marked decrease in the load showed that the maximum had been attained.

(d) COMPRESSIVE STRENGTH

The individual wall strengths, as well as the average value for any group of walls, are given in Table 9. The value of this table is largely as a compilation of data on the strength of brick walls, which differ as to the materials and the quality of workmanship used in their construction, and which may be duplicated in structures.

Since the selection of proper working stresses for brick masonry requires a knowledge of the principal factors that govern strength, the results given in Table 9 afford useful comparisons between the strength of the walls and the variables featuring their construction.

(e) THE COMPARATIVE STRENGTHS OF SOLID AND OF HOLLOW WALLS OF BRICK

In order to study the effect of design on the strength of brick masonry, the walls of series 2, alike in all respects except the type of wall built with spread mortar joints and aged under ordinary conditions, will first be considered.

The average results of the compressive tests of these brick walls are given in Table 10 and are shown graphically in Figures 30 and 31. Each value is the average for three similar walls.

The values of compressive strength, which are based on gross area, are the same as those in Table 9 and were obtained by dividing the maximum load on the specimens by the gross area. The net areas of the walls were calculated as the product of the actual width of the brick withes and the length of the walls. They are less than the gross areas because the thickness of the longitudinal vertical joint was not included. For the hollow walls these net areas represent the minimum area in compression and for the solid walls they represent the sums of the areas of the brick withes under compression. The gross and net areas are the same for the 4-inch economy wall.

TABLE 10.—*Average strength of the different types of brick walls of series 2*

CEMENT-LIME MORTAR

Type of wall	Mississippi brick		New England brick	
	Compressive strength based on—			
	Gross area	Net area	Gross area	Net area
	Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
8-inch solid	1,160	1,265	1,790	2,030
12-inch solid	1,300	1,450	1,890	2,180
8-inch all-rolok	765	1,345	875	1,570
12-inch all-rolok	705	1,270	740	1,350
8-inch all-rolok in Flemish bond	750	1,320	640	1,130
12-inch all-rolok in Flemish bond	675	1,220	830	1,560
8-inch rolok-bak	940	1,265	880	1,210
12-inch rolok-bak	850	1,280	965	1,480
4-inch economy	1,435	1,435	1,940	1,940

CEMENT MORTAR

Type of wall	Mississippi brick Gross area	Mississippi brick Net area	New England brick Gross area	New England brick Net area
8-inch solid	1,380	1,515	2,635	2,980
12-inch solid	1,640	1,820	2,790	3,200
8-inch all-rolok	920	1,630	955	1,710
12-inch all-rolok	800	1,450	870	1,610
8-inch all-rolok in Flemish bond	800	1,405	775	1,380
12-inch all-rolok in Flemish bond	710	1,285	940	1,760
8-inch rolok-bak	920	1,240	1,205	1,670
12-inch rolok-bak	940	1,420	1,590	2,460
4-inch economy	1,625	1,625	3,145	3,145

The compressive strengths in pounds per square inch of the three types of solid walls are about equal. It is especially noteworthy that the thin 4-inch economy walls, when concentrically loaded, withstood as high compressive stresses as did the walls 8 and 12 inches thick.

For the walls built of either Mississippi or New England brick the solid specimens withstood greater loads and greater stresses, based on gross area, than did the hollow walls. If the wall strength is a function of the area in compression, as may reasonably be supposed, the strengths, based on net areas, should be the same for all walls built of the same kind of brick and laid in the same kind of mortar. This is apparently true for the walls of Mississippi brick, as may be seen from Figure 30. The strength values listed under Mississippi brick, net area, in Table 10 are remarkably uniform for each mortar mixture, and it is apparent that the net areas of the walls built of Mississippi brick may be used as a basis of design for the hollow walls. These bricks were not warped, were fairly uniform in size, and had nearly perfectly rectangular cross sections.

The results of the tests of the hollow walls of New England brick, however, show that they do not have a constant compressive strength.

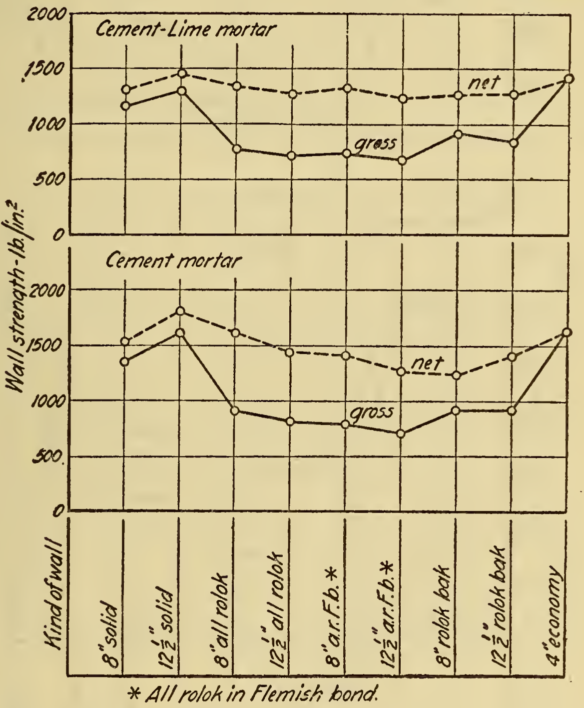


Figure 30.—*Average strength of the walls of series 2 built of Mississippi brick*

based on net area. Table 6 indicates that the various strength properties are from two to three times as much for the New England as for the Mississippi brick, while Table 10 shows that the solid walls of New England brick are considerably stronger than those of Mississippi brick. The strengths of the hollow walls are, however, not greatly different for the two kinds of brick.

The New England brick were not as regular in their shape as the other. The cross section of these brick was similar in shape to that shown in Figure 32, although the difference in width between top and bottom is much exaggerated. The difference in the top and bottom widths of these molded brick amounted to about 0.1 inch, and it may be that this lack of a truly rectangular cross section affected the wall strength when the brick was laid on the narrow edge as in the hollow walls.

Since the hollow walls of the strong New England brick are not much stronger than those built of the Mississippi brick, it must be concluded that the compressive and tensile strength and the modulus of rupture of the individual brick do not completely define the factors that have a determining influence on the strength of hollow masonry. Further research will be necessary before the strength of a hollow wall can be predicted from the strength of the brick and mortar.

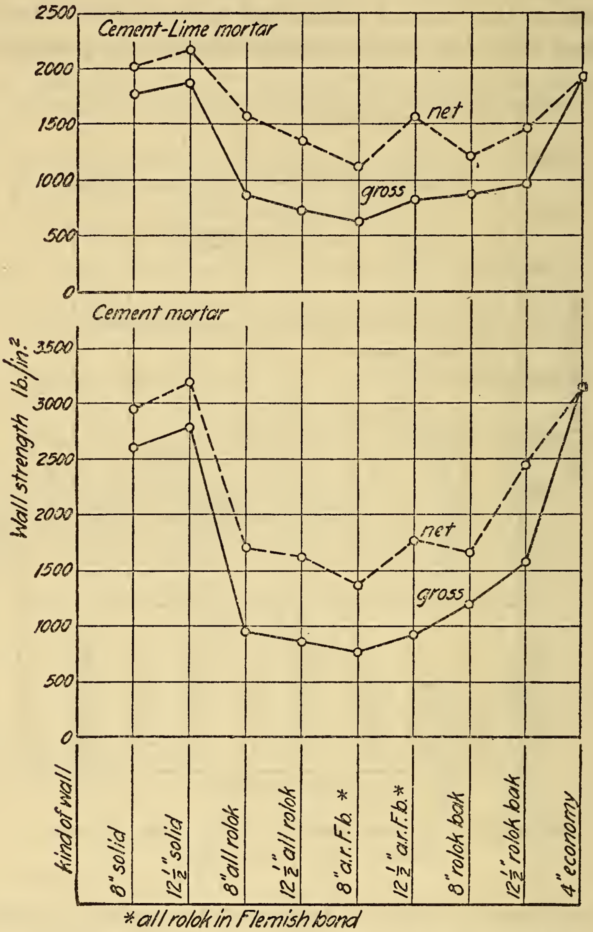


FIGURE 31.—*Average strength of the walls of series 2 built of New England brick*

In order to study the effect of type on wall strength when the walls were built with less care, those walls of series 1 listed in Table 11 will be considered.

TABLE 11.—*Strength of different types of walls of series 1*

[Brick, Mississippi; mortar, cement]

Type of wall	Wall No.	Wall strength based on—	
		Gross area	Net area
		Lbs./in.²	*Lbs./in.²*
8-inch solid	155	870	950
8-inch all-rolok	156	440	780
8-inch all-rolok in Flemish bond	157	535	940
8-inch rolok-bak	158	745	1, 010

Since only one wall of each type was tested, the results are not very conclusive, but, in general, they show the same trend as those for the walls of series 2 built of Mississippi brick. The solid wall withstood the greatest compressive stress, based on gross area, and the hollow walls were practically as strong as the solid, based on net area.

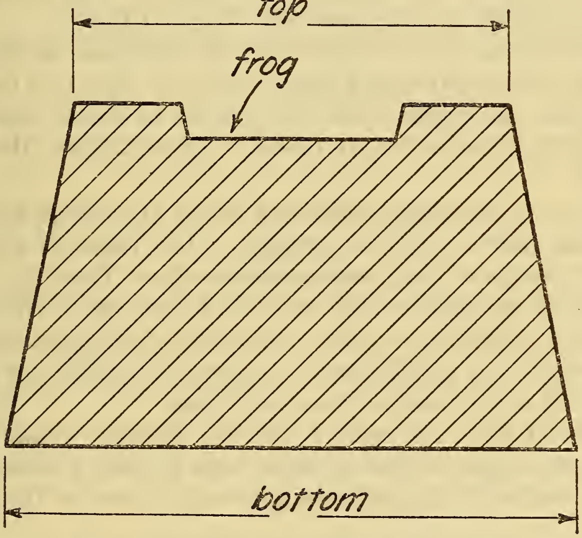


FIGURE 32.—*An exaggerated view of a cross section of an irregular brick*

The walls of series 1 had lower strengths than those of series 2, but the values given in Table 11 show that the hollow walls of brick may be safely used for many construction purposes.

(f) THE EFFECT OF MORTAR ON THE STRENGTH OF WALLS OTHERWISE SIMILAR

In series 1 the tests of the solid walls of Chicago brick afford comparisons from which the effect of the mortar on wall strength can be determined. The three mortar mixtures had very different compressive strengths as may be noted from Table 8. The strength of the solid walls (Table 9) varied about as the cube root of these mortar cylinder strengths. Although this is by no means to be taken as an exact relationship, the ratio of average wall strength to cube root of dry mortar cylinder strength is more constant for the three mixtures of mortar than any other simple relation which was tried.

The strengths of the mortar cylinders varied considerably from wall to wall with the same mixture, and only averages from a large number of cylinders can be said to have a significant value. In several of the groups of three walls which were alike in type of wall, mortar, workmanship, brick, curing conditions, etc., the difference in wall strength did not always follow in the same order as the differences in mortar cylinder strength. Furthermore, the increase in wall strength due to an increase in mortar strength was usually not as great with the Mississippi as with the stronger New England brick.

An attempt was made to determine the difference in wall strength produced by the addition of a small amount of lime to a cement mortar. For this comparison the two groups of 8-inch solid walls of Chicago brick in series 2 were made. Table 12 gives the results of these tests.

There was no significant difference either in average wall strength or in average mortar cylinder strength. The values of wall strength for the two groups overlap, as may be seen from Table 9.

In Table 13 are collected the results of the tests of the solid walls of series 2 for which the variables are kinds of brick and mortar.

The increase due to difference in mortar is greater for the strong New England brick than for the other kinds.

The ratio of the cube root of the dry mortar cylinder strengths (see Table 8) for the mortars of these walls is 1.38, a value within the range of variation of the wall strength ratios given in Table 13.

TABLE 12.—*Results of tests of walls with slight differences in the mortar mixtures*

[Wall type, 8-inch solid; brick, Chicago; series 2; workmanship, spread joints; curing conditions, ordinary.]

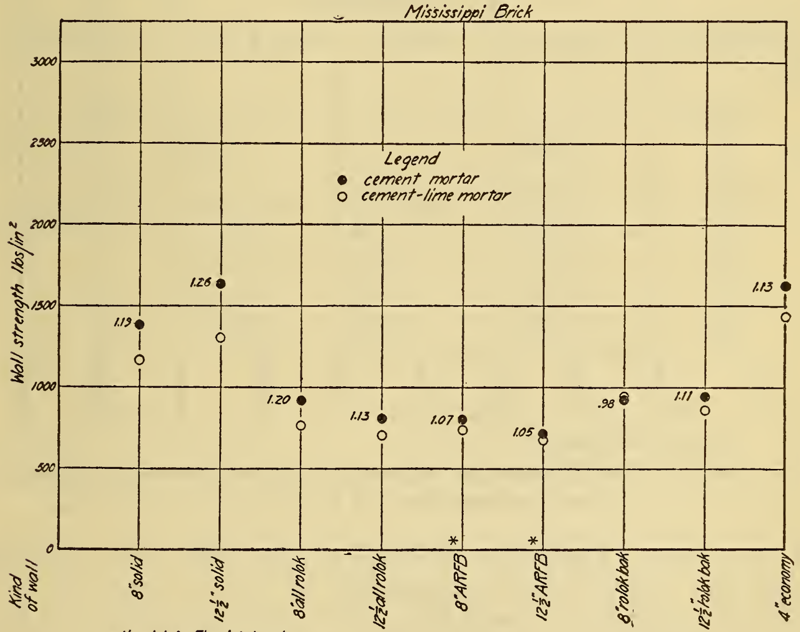
Wall Nos.	Mortar proportions (by volume)	Average wall strength	Average mortar cylinder strength	
			Wet	Dry
		Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*
160, 161, 162	1C: 3S	880	3,050	2,180
163, 164, 165	1C: 0.1L: 3S	855	3,580	2,350

TABLE 13.—*Results of tests of solid walls of series 2*

[Smooth spread mortar joints; ordinary curing conditions]

Type of wall	Kind of brick	Average wall strength		
		Cement-lime (*C-L*)	Cement (*C*)	Ratio $\frac{C}{C\text{-}L}$
		Lbs./in.^{2}	*Lbs./in.*^{2}	
8-inch solid	Detroit	910	1,080	1.19
	Mississippi	1,160	1,380	1.19
	New England	1,790	2,635	1.47
12-inch solid	Detroit	985	1,210	1.23
	Mississippi	1,300	1,640	1.26
	New England	1,890	2,790	1.48
4-inch economy	Mississippi	1,435	1,625	1.13
	New England	1,940	3,145	1.62

The effect of mortar on the strength of walls of different types is shown graphically in Figures 33 and 34 for the walls built of Mississippi and New England brick, respectively. The numbers placed beside the values for the cement mortar walls are the ratios of the wall strengths of cement mortar to those of cement-lime mortar. There appears to be no definite and consistent relation for the increase in strength due to the use of cement mortar, the increase being different from the



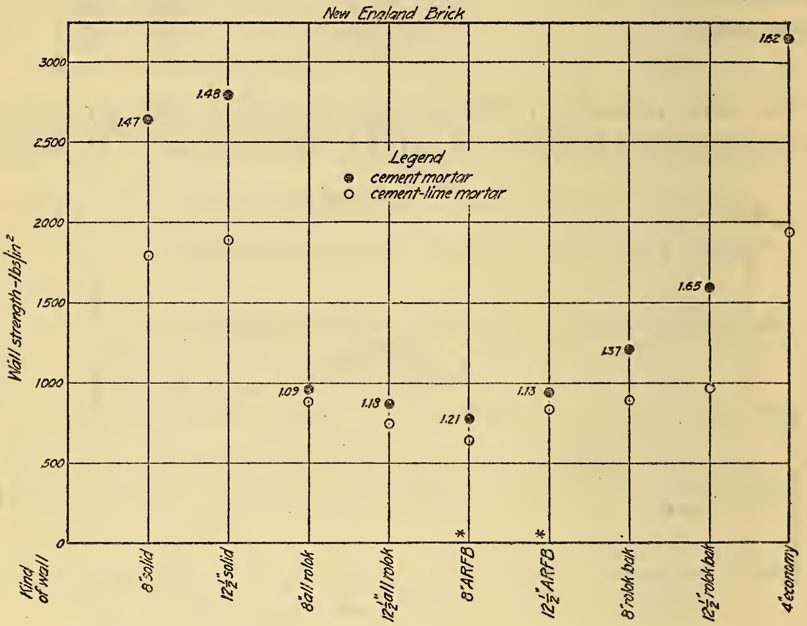
* all rolok in Flemish bond

FIGURE 33.—*The differences in wall strength due to differences in mortar for the walls of series 2 built of Mississippi brick*

different types of walls and usually being less for the Mississippi than for the stronger New England brick.

(g) THE EFFECT OF DAMP CURING ON THE COMPRESSIVE STRENGTH OF BRICK WALLS

One of the problems studied in this series of tests was to determine the effect of damp curing on the compressive strength of brick walls. At the time these tests were outlined there was a more or less general opinion that walls kept damp for a time after they had been built would be stronger than others allowed to age without wetting. Cylinders of Portland cement mortar (size 2 by 4 inches) aged for 60 days in water are about twice as strong as those kept in air, as may be noted from Table 8, and, consequently, it might be expected that conditions which tend to keep the mortar in the wall moist would also tend to increase its strength and therefore increase the strength of the wall.



*all rolok in Flemish bond

FIGURE 34.—*The differences in wall strength due to differences in mortar for the walls of series 2 built of New England brick*

Some walls of series 2, built with cement mortar, were allowed to age in the laboratory under ordinary conditions. Other similar walls listed in Tables 1 and 9 as "wetted" were covered with burlap, as shown in Figure 15. The burlap was kept damp for one week after the walls had been built and was then removed.

The results of these compressive tests of brick walls are given in Table 14.

It is seen from these data that there was no increase in the strength of the walls due to damp curing. Whether the same results would have been obtained on specimens built out of doors is, perhaps, open to question.

Although the strength of small mortar cylinders is increased by keeping them wet, there are several reasons why much greater strength in the wet walls than in the dry ones would not be expected.

In the first place, the failure in all of these walls laid in cement mortar occurred in the brick and not in the mortar. While walls similar in all respects, except as to mortar, will generally have the higher strengths with stronger mortars, the strength of the brick is probably the determining factor in wall strength when the mortars are of about the same strength.

TABLE 14.—*Effect of wetting on wall strength*

[Walls of series 2, cement mortar]

Type of wall	Kind of brick	Wall Nos.	Curing conditions	Average wall strength	Ratio of wall strengths, wetted/ ordinary
				Lbs./in.²	
8-inch solid	Detroit	22, 23, 24	Ordinary	1,080	
	----do	33	Wetted	1,055	0.98
12-inch solid	----do	28, 29, 30	Ordinary	1,210	
	----do	31, 32	Wetted	1,105	.91
	Mississippi	43, 44	Ordinary	1,785	
	----do	46, 47	Wetted	1,590	.89
	New England	103, 104	Ordinary	2,835	
	----do	106, 107	Wetted	2,510	.89
12-inch rolok-bak	Mississippi	82, 83	Ordinary	935	
	----do	85, 86	Wetted	965	1.03
	New England	142, 143	Ordinary	1,580	
	----do	145, 146	Wetted	1,325	.84

In the second place, it has been found that an increase in mortar strength is accompanied by a relatively smaller increase in wall strength if the same quality of brick is used.[8] Hence, a large increase in mortar strength is necessary to produce a notable increase in wall strength. This should not, however, be taken to mean that the mortar is not a very important factor in wall strength.

It is probable, moreover, that the wetting of the walls did not increase greatly the strength of the mortar, for although the wetting would tend to retard the evaporation of moisture, the loss of moisture from the walls in dry storage proceeded at a slow rate. The moisture present in the brick and mortar at the time the walls were built evaporated at such a slow rate as to provide sufficient moisture at early ages for favorable curing conditions, since in all of these

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[8] See data on wall strength and mortar strength in B. S. Tech. Paper No. 276, Compressive Strength of Sand-Lime-Brick Walls, by Whittemore and Stang.

walls the brick were probably wetter when laid than is the case in ordinary commercial practice.

Finally, a few samples of the mortar taken from these walls after test were found to contain, on the average, about 8 per cent of moisture by weight. This damp condition would tend to decrease the strength of the brick and of the mortar and, consequently, the strength of the damp cured walls. There are no definite data to show how much the strength of either the mortar or the brick was changed by the indefinite or rather nonuniform moisture content of the walls after they had aged. Numerous tests [9] have shown that Portland-cement mortars and concrete are considerably weakened when wetted just previous to testing.

The strength of some bricks is decreased by moisture. Others do not appear to have their strength influenced by this condition. Table 15 gives the compressive strengths of bricks used in this investigation when tested flatwise in the wet and dry condition, each value begin the average of 50 tests. The wet bricks had been immersed in water for 48 hours before test and were, of course, much wetter than were those in the walls at the time of test.

TABLE 15.—*Compressive strength of half brick wet and dry, flatwise*

Kind of brick	Compressive strength		Ratio wet/dry
	Wet	Dry	
	Lbs./in.²	*Lbs./in.²*	
Detroit	2, 520	3, 540	0. 71
Mississippi	3, 520	3, 410	1. 03
New England	6, 990	8, 600	. 81

The values given in Table 15, purporting to show the effect of moisture on the compressive strength of brick, probably indicate a somewhat greater decrease in strength due to moisture than actually existed because of the wet plaster of Paris cap. All of the bricks were capped with plaster of Paris prior to testing and, since the strength of gypsum is greatly decreased by moisture,[10] the weakening of the caps may have affected the results.

The Detroit and New England bricks were considerably weaker when wet, while the strength of the Mississippi brick did not appear to be affected by moisture. The slightly low compressive value for these brick dry is probably due to the sampling error and not to any real difference in their compressive strengths when in different moisture conditions. Reference to Table 14, however, shows that the wet

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[9] Herbert J. Gilkey, The Effect of Varied Curing Conditions Upon the Compressive Strength of Mortar and Concrete, Proc. Am. Concrete Inst., 22; 1926.

[10] W. A. Slater, Some Structural Properties of Gypsum and of Reinforced Gypsum, Trans. Ill. Acad. Sci., 9.

walls built of Detroit and New England bricks were only a little weaker relative to the companion dry walls than those built of Mississippi brick, the average ratios being 0.905 for the Detroit and New England and 0.960 for the Mississippi bricks.

Thus we have opposing effects which tend to keep the wall strength constant as between damp cured and dry walls. The dampness may tend to produce a stronger mortar, but the moisture present in the brick at the time of test weakens the wall.

It seems reasonable, then, to suppose that brick walls built with strong cement mortar and fairly wet brick will be as strong when aged in air for 60 days as they will be if they are kept damp for a short time after construction.

(h) THE EFFECT OF THE QUALITY OF WORKMANSHIP ON WALL STRENGTH

The workmanship typical of each of the two masons who built these brick walls has already been described in some detail and may be summarized as follows:

For walls of series 1, relatively high rate of laying brick, absence of mortar in the longitudinal vertical joints, and pronounced furrowing in the horizontal mortar beds; for walls of series 2, slow rate of laying brick, careful filling of the vertical joints, and smooth spread bed joints.

In Table 16 are listed those walls which show the effect of differences in workmanship. For the 8-inch solid walls of Chicago brick, the average thickness of the mortar joints was almost the same for both groups, and the 30 per cent increase in strength for the walls of series 2 must be attributed to the differences in workmanship.

The important differences as far as they could be observed consisted of the absence of furrowing of the horizontal mortar joints in series 2 and the better filling of the vertical joints. With the Mississippi brick, wall 155 of series 1 had exceptionally thick mortar joints (0.73 inch), and it may be that the greater strength of walls 37, 38, and 39, of 59 per cent, was due to their having thinner joints. The absence of furrowing and the filling of the vertical joints apparently made the 8-inch solid walls of New England brick and the 12-inch solid walls of Chicago brick of series 2 decidedly stronger than the companion walls of series 1.

The large increases in strength for the hollow walls of series 2 over the strengths of walls of series 1 was unexpected. It was supposed that the use of brick on edge in the construction of the hollow walls would not permit furrowing. However, demolition of these walls after testing showed that the mason furrowed the horizontal mortar bed on the narrow edge of the brick as consistently as on the regular solid construction. The furrow was continuous throughout the entire length of the mortar bed, but was broken up in much the same manner as were the furrows in the solid walls as shown in Figure 7.

The uneven and irregular bedding probably produced bending stresses in the bricks, which caused local concentrations of load and resulted in failure at lower loads than would have been the case with more even joints.

TABLE 16.—*Result of tests of brick walls with variations in workmanship*

[Cement mortar throughout]

Type of wall	Brick	Series 1 (furrowed joints)			Series 2 (spread joints)			Increase in wall strength, series 2 to series 1
		Wall No.	Average thickness of mortar joints	Wall strength	Wall No.	Average thickness of mortar joints	Wall strength	
			Inch	*Lbs./in.²*		*Inch*	*Lbs./in.²*	*Per cent*
8-inch solid	Chicago	13	0.56	660	160	0.57	800	
		14	.56	750	161	.59	870	
		15	.57	580	162	.55	965	
	Average		.56	665		.57	880	32
	Mississippi	155	.73	870	37	.52	1,335	
					38	.44	1,405	
					39	.40	1,405	
	Average					.45	1,380	59
	New England	154	.46	2,030	97	.36	2,040	
					98	.22	2,950	
					99	.27	2,915	
	Average					.28	2,635	30
12-inch solid	Chicago	16	.57	655	166	.49	890	
		17	.56	655	167	.51	1,080	
	Average		.56	655		.50	985	50
8-inch all-rolok	Mississippi	156	.66	440	52	.46	850	
					53	.40	735	
					54	.41	1,175	
	Average					.42	920	109
8-inch all-rolok in Flemish bond	Mississippi	157	.65	535	64	.47	825	
					65	.43	720	
					66	.43	855	
	Average					.44	800	50
8-inch rolok-bak	Mississippi	158	.62	745	76	.48	925	
					77	.42	890	
					78	.47	950	
	Average					.46	920	24

These comparisons of strengths of hollow walls lead to the belief that full spread horizontal mortar beds without furrowing are more important from a strength standpoint than the complete filling of vertical joints. In the hollow walls the longitudinal space between the rowlock wythes, of course, contained no mortar, and differences in strength were, therefore, almost entirely due to differences in the horizontal mortar beds.

The apparent effect of furrowing and unfilled vertical joints on wall strength is strikingly brought out by a comparison of the strengths of walls 155 and 159, as shown in Table 17. Both walls were built by the mason of series 1. Although wall 159, with no furrowing in the mortar beds, was built at an exceptionally fast rate, its strength was 70 per cent greater than that of wall 155 with the typical furrows.

TABLE 17.—*Effect of furrowing and unfilled vertical joints in walls of series 1*

[Type of wall, 8-inch solid; mortar, cement; brick, Mississippi]

Workmanship (type of bed joints)	Wall No.	Brick laid per hour	Average thickness of mortar joint	Wall strength
			Inch	*Lbs./in.*^{2}
Furrowed	155	195	0.73	870
Spread, no furrowing	159	264	.62	1,480
Ratio of wall strengths				1.70

The rate of laying wall 159, as given in Tables 3 and 17, and the statement of the mason who built the walls of series 2 show that spreading the mortar bed without furrowing does not reduce the rate of laying brick. The comparative results given in Tables 16 and 17 show the remarkable increase in strength obtained by the better filling of the mortar joints. It is believed that the realization of the importance of having smooth and level horizontal mortar beds in a brick wall is the most important conclusion of these tests. This construction practice, which apparently involves no increase in labor cost, but which results in a very significant increase in strength, is strongly recommended to builders of masonry structures.

A comparison of "spread" and "shoved" workmanship for walls of series 2 is afforded in Table 18. Wall 18 of Chicago brick and "shoved" workmanship had thinner mortar joints than did the companion walls 166 and 167 built of the same kind of brick with the full spread joints of series 2. In the three groups listed in Table 18 the walls of Chicago brick constitute the only group for which the "shoved" workmanship was superior to the other. The table shows that shoved work introduces no improvement in strength over the spread and fully slushed joint workmanship which was typical of series 2.

TABLE 18.—*Comparison of "spread" with "shoved" joints for walls of series 2*

[Type of walls, 12-inch solid; mortar, cement]

Kind of brick	"Spread" joints			"Shoved" joints			Ratio of wall strength "shoved" to "spread"
	Wall No.	Average thickness of mortar joint	Wall strength	Wall No.	Average thickness of mortar joint	Wall strength	
		Inch	*Lbs./in.*^{2}		*Inch*	*Lbs./in.*^{2}	
Chicago	166 167	0.49 .51	890 1,080	18	0.31	1,165	1.18
Average		.50	985				
Mississippi	43 44 45	.51 .37 .42	1,710 1,855 1,350	48	.42	1,465	.89
Average		.43	1,640				
New England	103 104 105	.28 .23 .23	2,440 3,230 2,695	108	.22	2,720	.97
Average		.25	2,790				

Reference has been made several times to the thickness of the mortar joints as having a possible effect on wall strength. Although this investigation was not planned with a view to having thickness of mortar joint a variable for the walls, Table 3 shows that some variation did exist. A study of the data for the single walls shows that joint thickness was by no means a controlling factor in strength for the hollow walls. The thickness of the beds in the groups of solid walls of series 1 was practically uniform from wall to wall and the results of these tests throw no light on this subject.

The thickness of the mortar joints and the wall strength are given in Table 19 for 18 groups of solid walls of series 2 built with comparable workmanship and aged under ordinary conditions. The walls of each group have been arranged in the order of wall strengths, and it might be expected that the wall having the least thickness of mortar joint would have the greatest strength. In the column designated "order" of this table those groups have been classed as "regular," for which increase in joint thickness is accompanied by decreases in wall strength, as "reverse," if increase in joint thickness is accompanied by increase in wall strength, and as "irregular" for the others which follow neither of these classifications entirely.

Table 19.—*Effect of thickness of mortar joints on strength of solid walls of series 2*

A. CEMENT-LIME MORTAR

Type of wall	Kind of brick	Wall No.	Average thickness of mortar joint	Wall strength	Order
			Inch	*Lbs./in.²*	
8-inch solid	Detroit	19 20 21	0.39 .40 .44	1,060 905 760	Regular.
	Mississippi	36 35 34	.40 .44 .56	1,340 1,175 965	Do.
	New England	95 94 96	.28 .35 .27	1,875 1,785 1,710	Irregular.
12-inch solid	Detroit	25 27 26	.38 .44 .38	1,050 965 940	Do.
	Mississippi	40 41 42	.50 .40 .44	1,375 1,305 1,225	Do.
	New England	101 102 100	.20 .25 .33	1,990 1,855 1,815	Regular.
4-inch economy	Mississippi	90 88 89	.42 .44 .40	1,565 1,370 1,365	Irregular.
	New England	149 148 150	.30 .36 .22	1,975 1,960 1,880	Do.

TABLE 19.—*Effect of thickness of mortar joints on strength of solid walls of series 2*—Continued

B. CEMENT MORTAR

Type of wall	Kind of brick	Wall No.	Average thickness of mortar joint	Wall strength	Order
			Inch	*Lbs./in.²*	
8-inch solid	Chicago	162	0.55	965	Irregular.
		161	.59	870	
		160	.57	800	
	do	164	.57	925	Regular.
		163	.62	885	
		165	.66	755	
	Detroit	22	.38	1,305	Irregular.
		24	.43	1,050	
		23	.40	895	
	Mississippi	38	.44	1,405	Do.
		39	.40	1,405	
		37	.52	1,335	
	New England	98	.22	2,950	Regular.
		99	.27	2,915	
		97	.36	2,040	
12-inch solid	Detroit	29	.37	1,345	Do.
		28	.39	1,165	
		30	.41	1,115	
	Mississippi	44	.37	1,855	Irregular.
		43	.51	1,710	
		45	.42	1,350	
	New England	104	.23	3,230	Regular.
		105	.23	2,695	
		103	.28	2,440	
4-inch economy	Mississippi	93	.46	1,875	Reverse.
		91	.44	1,650	
		92	.41	1,350	
	New England	152	.29	3,520	Irregular.
		153	.23	3,160	
		151	.35	2,755	

If there is only a chance relation between joint thickness and wall strength, it would be expected that the "regular" and the "reverse" order would each occur three times in the 18 groups. The table shows that, of the 18 groups, 7 are regular, or two and one-third times as many as would be expected from a chance distribution. Only one reverse group is present instead of the three to be expected. The tendency is therefore for walls with thin joints to have somewhat higher strengths, although it has been impossible to find a definite relationship between these two factors.

(i) THE RELATION OF STRESS AT FIRST CRACK TO MAXIMUM STRESS

Table 20 gives the ratio of the stress at first crack to the maximum stress for the walls of series 1 with furrowed joints and for those of series 2 with full-spread joints which were cured under ordinary conditions.

For the solid walls of series 1 it appears that these ratios become greater as the strength of the mortar increases. The average ratio for the Chicago brick walls of series 2 built with cement and cement-lime mortars is greater than for those of series 1 built with the same mortars.

The solid walls of Detroit and of New England brick, both of which had frogs, had initial signs of failure at considerably lower ratios than for the solid walls of the other kinds of brick. Whether this relatively low initial failure is due in part to the presence of the frog in these bricks and to the fact that they were more irregular in size and shape than the Chicago and Mississippi bricks is unknown.

TABLE 20.—*Relation of stress at first crack to wall strength*

[Ordinary curing conditions]

Description of groups compared	Number of walls averaged	Stress at first crack/wall strength
Series 1 (furrowed joints):		*Ratio*
Lime-mortar walls, Chicago brick	6	0.71
Cement-lime mortar walls, Chicago brick	6	.88
Cement mortar walls, Chicago brick	5	.94
All walls, Chicago brick	17	.84
Series 2 (full spread joints):		
Solid walls of Chicago brick	8	.96
Solid walls of Detroit brick	12	.64
Solid walls of Mississippi brick	18	.92
Solid walls of New England brick	18	.68
Solid walls	56	.79
All-rolok walls	24	.70
All-rolok in Flemish bond walls	24	.74
Rolok-bak walls	24	.72
Walls of Mississippi brick	54	.83
Walls of New England brick	54	.67
Walls built with cement-lime mortar	60	.72
Walls built with cement mortar	68	.78

Table 20 shows that the solid walls had a somewhat higher ratio between stress at first crack and maximum stress than the hollow walls. The ratios were about the same for the different types of hollow walls.

The walls of series 2 built with cement mortar had a higher ratio than those built with cement-lime mortar, the relative values being much the same as for walls of series 1.

It is evident from a study of Table 20 that the relation of stress at first crack to wall strength is not a constant, but varies with many of the conditions that affect wall strength.

4. WALLETTES

The results of the compressive tests of the wallettes are given in Table 21. The wallettes were built by the same mason and cured under the same conditions as the walls of the corresponding numbers. Most of the wallettes were built either on the same day as the walls or on the day after.

TABLE 21.—*Results of compressive tests of brick wallettes (gross area)*

A. WALLETTES OF SERIES 1

Type of wallette	Mortar	Kind of brick	Wallette Nos.			Average stress at first crack	Wallette strength			
			a	b	c		a	b	c	Average
						Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
8-inch solid	Lime	Chicago	1	2	3	245	380	375	350	370
	Cement-lime	do	7	8	9	550	735	725	685	715
	Cement	do	13	14	15	665	780	885	700	790
12-inch solid	Lime	do	4	5	6	235	420	410	405	410
	Cement-lime	do	10	11	12	580	625	680	660	655
	Cement	do	16	17	-----	690	700	810	----------	755

B. WALLETTES OF SERIES 2

Type of wallette	Mortar	Kind of brick	Wallette Nos.			Average stress at first crack	Wallette strength			
			a	b	c		a	b	c	Average
8-inch solid	Cement-lime	Detroit	19	20	21	695	1,315	705	1,120	1,045
		Mississippi	34	35	36	1,265	1,020	1,425	1,795	1,410
		New England	94	95	96	1,405	1,730	2,850	2,320	2,300
	Cement	Detroit	22	23	24	1,210	1,335	1,045	1,675	1,350
		do	33	-----	-----	765	865	----------	----------	865
		Mississippi	37	38	39	1,405	1,550	1,730	1,615	1,620
		New England	97	98	99	2,080	3,455	3,880	3,760	3,700
12-inch solid	Cement-lime	Detroit	25	26	27	865	1,265	950	845	1,020
		Mississippi	40	41	42	1,175	1,390	1,210	1,230	1,275
		New England	100	101	102	1,625	1,965	2,845	2,565	2,460
	Cement	Chicago	18	-----	-----	1,145	1,190	----------	----------	1,190
		Detroit	28	29	30	1,200	1,605	1,620	785	1,335
		do	31	32	-----	745	1,225	1,100	----------	1,160
		Mississippi	43	44	45	1,605	1,725	2,060	1,500	1,760
		do	46	47	-----	1,410	1,425	2,305	----------	1,865
		do	48	-----	-----	1,350	1,640	----------	----------	1,640
		New England	103	104	105	2,190	2,515	4,140	3,425	3,360
		do	106	107	-----	1,950	2,355	3,790	----------	3,075
		do	108	-----	-----	2,440	3,200	----------	----------	3,200
8-inch all-rolok	Cement-lime	Mississippi	49	50	51	510	805	845	895	850
		New England	109	110	-----	395	1,385	2,015	----------	1,700
	Cement	Mississippi	52	53	54	735	990	800	1,280	1,025
		New England	112	113	114	630	1,465	1,995	1,520	1,660

TABLE 21.—*Results of compressive tests of brick wallettes (gross area)*—Continued

B. WALLETTES OF SERIES 2—Continued

Type of wallette	Mortar	Kind of brick	Wallette Nos.			Average stress at first crack	Wallette strength			
			a	b	c		a	b	c	Average
						Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
12-inch all-rolok	Cement-lime	Mississippi	55	56	57	735	720	1,115	755	865
		New England	115	116		715	825	1,535		1,180
	Cement	Mississippi	58	59	60	695	900	820	1,030	920
		New England	118	119		650	1,480	1,390		1,435
8-inch all-rolok in Flemish bond	Cement-lime	Mississippi	61	62	63	645	1,000	1,270	965	1,075
		New England	121	122		820	1,685	1,665		1,675
	Cement	Mississippi	64	65	66	670	955	1,135	870	990
		New England	124	125		820	1,740	1,080		1,410
12-inch all-rolok in Flemish bond	Cement-lime	Mississippi	67	68	69	595	875	990	1,215	1,030
		New England	127	128		795	1,650	1,510		1,580
	Cement	Mississippi	70	71	72	760	980	1,010	1,090	1,025
		New England	130	131		695	1,470	1,790		1,630
8-inch rolok-bak	Cement-lime	Mississippi	73	74	75	730	980	950	1,020	985
		New England	133	134		640	1,230	2,130		1,680
	Cement	Mississippi	76	77	78	785	850	1,255	1,405	1,170
		New England	136	137		805	1,255	3,150		2,205
12-inch rolok-bak (heavy duty)	Cement-lime	Mississippi	79	80	81	565	890	835	880	870
		New England	139	140		625	1,125	1,290		1,205
	Cement	Mississippi	82	83	84	645	770	1,040	1,125	980
		do	85	86		675	775	855		815
		New England	142	143		770	1,325	2,180		1,755
		do	145	146		815	2,370	2,275		2,320
12-inch rolok-bak (standard)	Cement	Mississippi	87			830	1,090			1,090

The area of the wallettes was taken as the product of the average thickness of the wallette by the minimum length. Figure 18 shows that in small specimens, with the brick clipped as little as possible, the length of the wallette may vary considerable from course to course. The values of wallette strength given in Table 21 are therefore based on minimum gross areas for the hollow as well as for the solid wallettes.

The compressive strength of the wallettes varied with the physical properties of the brick, with the type of construction, with the mortar, curing conditions, and workmanship very much as did the wall strengths.

The variation in strength from wallette to wallette in any group was much less for the specimens of series 1 than of series 2. The mason who built the specimens of series 2 did not seem to like to build the small walls and on several occasions had to be told to use as much care on them as he used on the larger specimens. The average fractional deviation of the strength values within a given group from the average was for the wallettes of series 1, 0.04, and for those of series 2 it amounted to 0.13. In drawing conclusions from the tests of series 2 it is therefore to be remembered that relatively large variations have occurred in many of the groups.

The differences in strength due to differences in the kind of brick are found only for the wallettes of series 2. All bricks for the wallettes of series 2 were soft-mud or dry-press bricks, except in the wallette 18 of Chicago brick. In all cases where groups of solid wallettes differing only in the kind of brick are compared, the New England specimens were strongest, followed in order by those of Mississippi and of Detroit brick.

As with the larger walls, the solid wallettes were stronger, based on gross area, than were any of the hollow types. The strengths based on net area were nearly the same irrespective of the type of construction for wallettes built of Mississippi brick and, while not so uniform for the wallettes of New England brick, were much more constant than for the walls previously discussed.

Table 22 shows the relative strength of the different types of walls and wallettes, the strongest being listed at the top in each group and the others in the order of their strengths. In six of the eight wall groups the types rank solid, rolok-bak, all-rolok, and all-rolok in Flemish bond, and in the two cases where this order does not hold the inversions are due to relatively small differences in strength—less than 100 lbs./in.^{2}. From the wallette tests, however, this arrangement in the order for the strengths of the different types would not be evident. In fact, only two groups of wallettes show this same order while four wallette groups rank—solid, all-rolok in Flemish bond, rolok-bak, and all-rolok. The fact that the solid wallettes were stronger than any of the hollow types shows, however, that larger strength differences are readily recognized from wallette tests.

TABLE 22.—*Relative strength of different types of walls and wallettes*

Wall thickness	Mortar	Strength rank			
		Mississippi		New England	
		Wall	Wallette	Wall	Wallette
8-inch	Cement-lime	Solid	Solid	Solid	Solid.
		Rolok-bak	A. r. F. b	Rolok-bak	All-rolok.
		All-rolok	Rolok-bak	All-rolok	Rolok-bak.
		A. r. F. b	All-rolok	A. r. F. b	A. r. F. b.
	Cement	Solid	Solid	Solid	Solid.
		Rolok-bak	Rolok-bak	Rolok-bak	Rolok-bak.
		All-rolok	All-rolok	All-rolok	All-rolok.
		A. r. F. b	A. r. F. b	A. r. F. b	A. r. F. b.
12-inch	Cement-lime	Solid	Solid	Solid	Solid.
		Rolok-bak	A. r. F. b	Rolok-bak	A. r. F. b.
		All-rolok	Rolok-bak	A. r. F. b	Rolok-bak.
		A. r. F. b	All-rolok	All-rolok	All-rolok.
	Cement	Solid	Solid	Solid	Solid.
		Rolok-bak	A. r. F. b	Rolok-bak	Rolok-bak.
		All-rolok	Rolok-bak	A. r. F. b	A. r. F. b.
		A. r. F. b	All-rolok	All-rolok	All-rolok.

A. r. F. b.=all rolok in Flemish bond.

For the solid wallettes the results given in Table 21 show that the mortar had about the same effect on wallette strength as on wall strength. The lime-mortar specimens were weakest and the cement-mortar specimens strongest for all groups of solid wallettes which differed only in the mortar mixtures used.

Keeping the wallettes damp for seven days after construction did not make them stronger than similar specimens cured under ordinary conditions except for the group for 12-inch rolok-bak wallettes of New England brick (Table 23). Specimens 142 and 143, cured under ordinary conditions, had an average strength of 1,755 lbs./in.^{2}, while the similar wallettes, 145 and 146, which were damp cured, had a strength of 2,320 lbs./in.^{2}. In the other five comparable groups the ratio of wallette strengths, damp cured to ordinary, ranged from 0.64 for the 8-inch solid wallettes of Detroit brick to 0.99 for the 12-inch solid specimens of Mississippi brick.

TABLE 23.—*Effect of wetting on wallette strength*

[Wallettes of series 2, cement mortar]

Type of walette	Kind of brick	Wallette Nos.	Curing conditions	Average wallette strength	Ratio of wallette strengths wetted/ordinary
				Lbs./in.^{2}	
8-inch solid	Detroit	22, 23, 24	Ordinary	1, 350	0. 64
		33	Wetted	865	
12-inch solid	do	28, 29, 30	Ordinary	1, 335	. 87
		31, 32	Wetted	1, 165	
	Mississippi	43, 44	Ordinary	1, 890	. 99
		46, 47	Wetted	1, 865	
	New England	103, 104	Ordinary	3, 330	. 92
		106, 107	Wetted	3, 075	
12-inch rolok-bak (heavy-duty)	Mississippi	82, 83	Ordinary	905	. 90
		85, 86	Wetted	815	
	New England	142, 143	Ordinary	1, 755	
		145, 146	Wetted	2, 320	1. 32

The only comparison due to difference in the workmanship is between wallette 18 of series 2 built with shoved workmanship and wallettes 16 and 17 of series 1 with the typical furrowed joint workmanship of this series. The relative strengths are as 1,190 is to 755, giving an increase in strength with shoved joints of 58 per cent over that obtained with furrowed joints.

A study of the relation between stress at first crack and wallette strength shows that the same conclusions may be drawn as from the wall tests. The main difference between the wall and wallette results is that the hollow wallettes had considerably lower ratio of stress at first crack to final strength than was found from the wall tests.

The lowering of the ratio for strength at first crack to ultimate strength of hollow wallettes is brought about not by the strength at first crack being low, but by the ultimate strength being high as compared with the corresponding hollow walls. The difference in behavior of hollow walls and wallettes is apparently explainable by considering the relative slenderness ratios of the withes when the connecting headers are broken. For hollow walls (all-rolok or all-rolok in Flemish bond) when the headers are broken, there results two unsupported sections 9 feet high by 2¼ inches thick. Through column action these collapse. The wallettes, however, give sections 34 inches by 2¼ inches. This gives a slenderness ratio so low that column action does not take place and the load increases to the point where crushing of the brick results. The values for slenderness ratios ($1/r$) for wall and wallette sections (108 inches by 2¼ inches and 34 inches by 2¼ inches) are 166 and 52.4, respectively.

Table 24 gives average values of the ratio of wall strength to wallette strength. These values show that the ratio (for the solid specimens for series 2) becomes less as stronger brick are used. In other words, the use of strong brick gives a greater increase in wallette strength than in wall strength.

In Figure 35 are plotted the solid wall strengths against the solid wallette strengths for each group in both series for which direct comparisons can be made. The average ratio from Table 24, represented by the diagonal line in the figure, of the wall strength to the wallette strength is 0.86, but the plotted points indicate the trend toward proportionately greater wallette strength for the stronger specimens. The ratio for the solid and rolok-bak specimens is greater than for those types in which all the withes are laid on edge.

The average values of the ratio of wall strength to wallette strength are about the same when the specimens are laid in cement-lime mortar as in cement mortar.

TABLE 24.—*Relation of wall to wallette strengths*

Description of groups compared	Wall strength / Wallette strength
	Ratio
Average for all solid specimens of both series	0.86
Series 2:	
Solid specimens of Detroit brick	.93
Solid specimens of Mississippi brick	.90
Solid specimens of New England brick	.79
Solid specimens	.87
All-rolok specimens	.75
All-rolok in Flemish bond specimens	.63
Rolok-bak specimens	.86
Specimens laid in cement-lime mortar	.78
Specimens laid in cement mortar	.81

In general, then, it may be stated that solid wallette strengths are affected by differences in brick, mortar, curing conditions, and workmanship in very much the same way as are solid wall strengths. In fact, the general tendencies of strength changes for the hollow specimens are also indicated by wallette strengths. For the hollow specimens the relation between the strengths of the wallettes and the walls is not as well defined, but the wallette strengths may serve as a measure of the strengths of both types of walls.

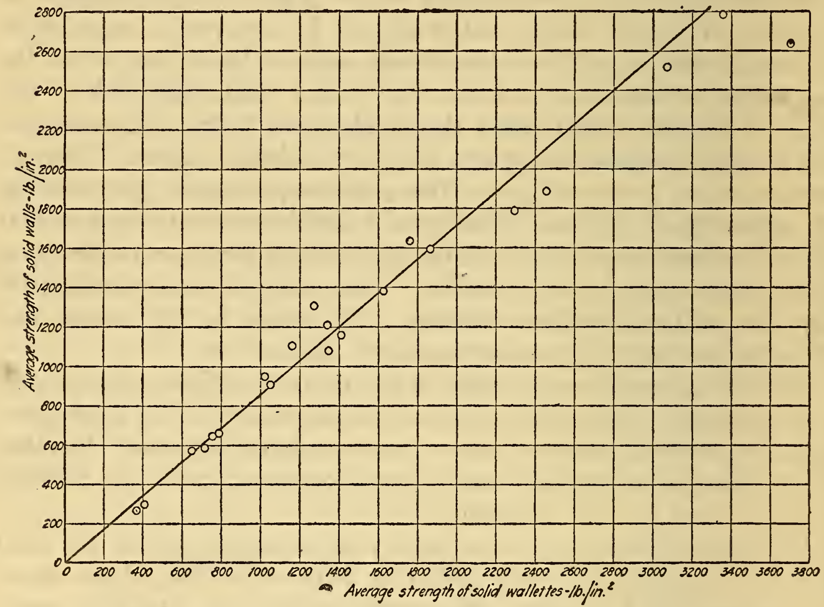

FIGURE 35.—*Relation of wall to wallette strengths for solid specimens*

5. RELATIONS BETWEEN THE STRENGTHS OF THE WALLS AND THE STRENGTHS OF THE BRICKS AND WALLETTES

The object of the tests of these brick walls was to find, if possible, some strength property of the bricks or of smaller walls which will be a measure of the strength of the solid walls. The ratios of the compressive strengths of the walls to the various properties of the bricks and to the compressive strengths of the wallettes are given in Table 25. This table is divided into seven groups, in each group of which the variable is the kind of brick. The ratio of wall strength to brick or wallette strength, of course, varies from group to group because of differences in mortar or in workmanship, but in any one group that ratio is the best measure of wall strength which is most nearly constant for the different kinds of bricks. A measure of the constancy of this ratio is given by dividing the mean deviation of the separate ratios by the mean of the ratios in a group. The smaller this value is the better this property of the brick serves as a measure of wall strength. Actually the magnitudes of the deviations of these ratios from their mean are measures of the degree to which the values for wall strength deviate from a linear relation with the particular brick strength to which they refer. If a much wider range in brick strengths had been involved, it is possible that the determination of the properties of brick which were the most consistent measures of wall strength should be based upon the consistency of the data with respect to a more general form of relationship that might not necessarily be linear.

TABLE 25.—*Relation of wall strength to strength of bricks and wallettes*

Group	Kind of brick	Wall Nos.	Number of walls in average	Average wall strength[1]	Ratios and their deviations of the compressive strengths of the walls to—											
					Compressive strength of half bricks flatwise [2]		Compressive strength of half bricks edgewise [2]		Modulus of rupture of bricks flatwise [2]		Tensile strength of bricks [2]		Shearing strength of bricks [2]		Compressive strength of wallettes [3]	
					Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean
				Lbs./in.^{2}												
A. 8 and 12 inch solid walls of series 1, lime mortar.	Chicago	1 to 6	6	287	0.088	0.09	0.086	0.10	0.23	0.40	0.69	0.35	0.26	0.02	0.74	0.01
	Sand-lime	1 to 6	6	302	.073		.109		.54		1.44		.25		.72	
B. 8 and 12 inch solid walls of series 1, cement-lime mortar.	Chicago	7 to 12	6	587	.18	.09	.18	.10	.48	.40	1.4	.36	.53	.02	.86	.10
	Sand-lime	7 to 12	6	622	.15		.22		1.11		3.0		.51		.71	
C. 8 and 12 inch solid walls of series 2, cement-lime mortar.	Detroit	19 to 21 and 25 to 27	6	945	.27	.18	.29	.27	1.4	.07	4.3	.12	.81	.17	.92	.08
	Mississippi	34 to 36 and 40 to 42	6	1,230	.36		.34		1.5		3.9		.77		.92	
	New England	94 to 96 and 100 to 102	6	1,840	.21		.16		1.2		3.1		.52		.77	
D. 4-inch solid walls of series 2, cement-lime mortar.	Mississippi	88 to 90	3	1,430	.42	.29	.39	.39	1.7	.13	4.5	.17	.90	.24	------	--------
	New England	148 to 150	3	1,940	.23		.17		1.3		3.2		.55		------	
E. 8 and 12 inch solid walls of series 1, cement mortar.	Chicago	13 to 17	5	660	.20	.09	.20	.20	.54	.29	1.6	.28	.60	.10	.85	.06
	Mississippi	155	1	870	.26		.24		1.06		2.7		.55		------	
	New England	154	1	2,030	.24		.18		1.31		3.4		.57		------	
	Sand-lime	13 to 18	6	905	.22		.33		1.62		4.3		.74		.76	
F. 8 and 12 inch solid walls of series 2, cement mortar.	Chicago	160 to 167	8	897	.27	.15	.27	.20	.73	.26	2.2	.24	.82	.10	------	.05
	Detroit	22 to 24 and 28 to 30	6	1,145	.32		.35		1.71		5.2		.98		.85	
	Mississippi	37 to 39 and 43 to 45	6	1,510	.44		.42		1.84		4.8		.95		.89	
	New England	97 to 99 and 103 to 105	6	2,710	.32		.24		1.75		4.5		.76		.77	
G. 4-inch solid walls of series 2, cement mortar.	Mississippi	91 to 93	3	1,625	.48	.14	.45	.25	2.0	0.00	5.1	.01	1.02	.07	------	--------
	New England	151 to 153	3	3,145	.37		.27		2.0		5.2		.89		------	
Weighted average	------	------	------	------	------	.14	------	.22	------	.22	------	.22	------	.11	------	.06

[1] Averaged from values given in Table 9 of this paper for all but the sand-lime brick. The values for sand-lime brick are given in Table 5, p. 65, Technologic Paper No. 276.
[2] Averaged from values given in Table 6 of this paper for all but the sand-lime brick. The values for sand-lime brick are given in Table 3, p. 62, Technologic Paper No. 276.
[3] Averaged from values given in Table 21 of this paper for all but the sand-lime brick. The values for sand-lime brick are given in Table 7, p. 70, Technologic Paper No. 276.

For the range in strengths found in these tests, however, it is believed that the basis of comparison used does not involve errors sufficiently large to affect the conclusions stated.

The walls of series 1, which were built of Chicago brick, are directly comparable to the sand-lime brick walls (see footnote 6, p. 518) which had previously been tested at the Bureau of Standards. These comparisons are given in groups A, B, and E for the different mortars. The ratios for compressive strength of half brick flatwise, shearing strength, and wallette strength are more constant than for the other brick strength ratios.[11]

In groups C, D, and G, where the bricks are all molded, the ratio of wall strength to modulus of rupture flatwise is the most constant of all the brick-strength ratios, and this would also be true for groups E and F if the end-cut Chicago bricks were excluded.

For the latter, the transverse strength is high in comparison with the compressive strength (Table 7), and with this brick the wall strength was quite apparently determined more by the compressive strength than the other.

The weighted averages of the mean deviations divided by the mean, calculated by giving the value for each group a weight proportional to the number of ratios in that group, are also given in Table 25 for the different ratios. A comparison of these weighted average values shows that the shearing strength appears to be the best brick-strength property for predicting the strength of the wall. It must be pointed out, however, that the values given in Table 6 for shearing strength represent only a small number of samples as compared to the other brick-strength values and that the shearing tests were made on specimens which differed in thickness.

The compressive strength of the half brick flatwise is the next best measure of wall strength after the shearing strength, for its mean deviation divided by mean of 0.14 is considerably less than for the compressive strength edgewise, modulus of rupture, or tensile strength.

On the average, however, the compressive strength of the wallettes is by far the most consistent value for determining wall strengths.

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[11] In the paper by J. W. McBurney entitled "The Effect of Strength of Brick on Compressive Strength of Brick Masonry," Proc. Am. Soc. Testing Materials, 28, Pt. II, p. 605, 1928, somewhat similar comparisons were made, but the conclusion was drawn that the compressive strength (flatwise) of the bricks was the most consistent measure of the strength of the walls. Because of an error in calculations, which was discovered after that paper had been published, the values given for the shearing strengths for all bricks except the sand-lime were double the true values, and for this reason, the strengths of the bricks in shear was not found to be closely related to the strength of the walls. The values given in McBurney's paper for the other strength properties of the bricks differ slightly in some cases from those given in the present paper. This, however, is due to the fact that, in the previous paper, a study was made of methods of sampling and some of the values given were the averages of more than one sample, whereas those given in the present paper are the results of tests of samples selected specifically for the investigation reported herein. Had there been no error in the data on the shearing strength of the bricks, there would have been no essential difference in the numerical data of the two reports.

The mean deviation divided by the mean value is consistently low for each of the five groups as well as having a weighted average value of only about half that of the best brick-strength property.

A large number of testing machines are now available in the United States which may be used for wallette tests. The tests of wallettes built of the brick to be used and laid in the mortar mixture specified can confidently be expected to give strength values which will seldom exceed the strength of a large wall by as much as 25 per cent. The prediction of wall strength from any brick strength value appears to be very uncertain because of differences in the method of manufacture of the brick and because different factors must be used for different mortars and workmanships.

Table 26 gives the relation between wall stress at first crack and the various strength properties of the bricks and to the strength of the wallettes. The weighted average values of mean deviation to mean show that the wallette strength is a better measure of wall stress at first crack than are any of the brick strengths. Of the brick strengths the shearing strength was the most consistent measure and there was no important difference in the consistencies obtained for the other strength properties.

TABLE 26.—*Relation of wall stress at first crack to strength of bricks and wallettes*

Group	Kind of brick	Wall Nos.	Number of walls in average	Average wall stress at first crack [1]	Ratios and their deviations of the wall stress at first crack to—											
					Compressive strength of half bricks, flatwise [2]		Compressive strength of half bricks, edgewise [2]		Modulus of rupture of bricks, flatwise [2]		Tensile strength of bricks [2]		Shearing strength of bricks [2]		Compressive strength of wallettes [3]	
					Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean	Ratio	Mean deviation/mean
				Lbs./in.^{2}												
A. 8 and 12 inch solid walls of series 1, lime mortar.	Chicago	1 to 6	6	205	0.062	0.11	0.61	0.10	0.17	0.37	0.49	0.34	0.19	0.06	0.53	0.03
	Sand-lime	1 to 6	6	208	.050		.75		.37		.99		.17		.50	
B. 8 and 12 inch solid walls of series 1, cement-lime mortar.	Chicago	7 to 12	6	515	.16	.14	.15	.09	.42	.37	1.2	.33	.47	.07	.75	.10
	Sand-lime	7 to 11	5	510	.12		.18		.91		2.4		.41		.61	
C. 8 and 12 inch solid walls of series 2, cement-lime mortar.	Detroit	19 to 21 and 25 to 27	6	553	.16	.40	.17	.41	.83	.29	2.5	.22	.47	.28	.54	.24
	Mississippi	34 to 36 and 40 to 42	6	1,140	.33		.31		1.39		3.6		.72		.85	
	New England	94 to 96 and 100 to 102	6	1,134	.13		.10		.73		1.9		.32		.48	
D. 4-inch solid walls of series 2, cement-lime mortar.	Mississippi	88 to 90	3	1,373	.40	.48	.38	.55	1.68	.35	4.3	.34	.86	.42	------	--------
	New England	148 to 150	3	1,233	.14		.11		.80		2.1		.35		------	
E. 8 and 12 inch solid walls of series 1, cement mortar.	Chicago	13 to 17	5	624	.19	.16	.19	.21	.51	.23	1.5	.20	.57	.10	.80	.15
	Mississippi	155	1	870	.26		.24		1.06		2.7		.55		------	
	New England	154	1	1,500	.17		.13		.97		2.5		.42		------	
	Sand-lime	13 to 18	6	700	.17		.25		1.25		3.3		.57		.59	
F. 8 and 12 inch solid walls of series 2, cement mortar.	Chicago	160 to 167	8	856	.26	.21	.26	.19	.70	.22	2.1	.18	.78	.13	------	.14
	Detroit	22 to 24 and 28 to 30	6	795	.22		.24		1.19		3.6		.68		.59	
	Mississippi	37 to 39 and 43 to 45	6	1,330	.39		.37		1.62		4.2		.84		.78	
	New England	97 to 99 and 103 to 105	6	2,028	.24		.18		1.31		3.4		.57		.57	
G. 4-inch solid walls of series 2, cement mortar.	Mississippi	91 to 93	3	1,575	.46	.28	.43	.37	1.9	.12	5.0	.14	.99	.21	------	--------
	New England	151 to 153	3	2,274	.26		.20		1.5		3.8		.64		------	
Weighted average			------	---------	-------	.25	------	.27	------	.27	------	.24	------	.17	------	.14

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[1] Averaged from values given in Table 9 of this paper for all but the sand-lime brick. The values for sand-lime brick are given in Table 5, p. 65, Technologic Paper No. 276.

[2] Averaged from values given in Table 6 of this paper for all but the sand-lime brick. The values for sand-lime brick are given in Table 3, p. 62, Technologic Paper No. 276.

[3] Averaged from values given in Table 21 of this paper for all but the sand-lime brick. The values for sand-lime brick are given in Table 7, p. 70, Technologic Paper No. 276.

V. CONCLUSIONS

The results of these compressive tests of 168 walls and of 129 wallettes, built of 4 kinds of common brick laid in 3 mortar mixtures, with 10 types of wall construction, with differences in workmanship and in curing conditions lead to the following conclusions:

1. The average strengths of solid walls built of end-cut Chicago brick (average compressive strength of half bricks flatwise, 3,280 lbs./in.^{2}) were as follows:

Lime mortar walls, 287 lbs./in.^{2}.
Cement-lime mortar walls, 587 lbs./in.^{2}.
Cement mortar walls, 661 lbs./in.^{2}.

A contract for building these walls was let, on a lump-sum basis, to a brick mason who specialized in small contracts. The work was done without supervision and was characterized by absence of mortar in the longitudinal vertical joints and deep furrowing of the horizontal beds.

2. With carefully supervised workmanship, the average strengths of solid walls, which were built by another mason hired by the day without regard to output and which had completely filled vertical joints and smooth spread horizontal mortar beds, were as follows:

Kind of brick	Compressive strength of half brick, flatwise	Average compressive strength of solid walls	
		Cement-lime mortar	Cement mortar
	Lbs./in.^{2}	*Lbs./in.^{2}*	*Lbs./in.^{2}*
Chicago	3, 280	-------------	895
Detroit	3, 540	945	1, 145
Mississippi	3, 410	1, 300	1, 550
New England	8, 600	1, 875	2, 855

3. The strengths of the solid walls were more closely related to the shearing strength of the bricks than to any other strength property measured. The compressive strength of the half bricks flatwise appeared to be the next best measure and was better than the compressive strength on edge, the modulus of rupture, or the tensile strength of the bricks.

4. On the average, the compressive strength of the wallettes was by far a more consistent measure of the strength of the walls than any of the brick strength values. In predicting wall strengths from brick strengths, effects of mortar and workmanship must be taken into account, while from wallette strengths only a single value need be determined. These tests show that the average strength of the walls was from about 60 to 90 per cent of the average wallette strength.

5. The strength of the solid walls, which were built by contract, varied about as the cube root of the compressive strength of the mortar cylinders (2 inches in diameter and 4 inches long) which were made

from the mortar of the walls and cured under the same conditions. For the solid walls, built under careful supervision, the increase in strength for cement-mortar walls over those laid in cement-lime mortar was about 20 per cent for walls of Detroit and Mississippi brick and about 50 per cent for walls of New England brick, while the average ratio of the cube roots of the mortar cylinder strengths (cement and cement-lime mortars) was 1.38.

6. With brick the cross sections of which closely approximated rectangles the strengths of the hollow walls varied about as the net areas in compression. When the brick were warped, the strength of the hollow walls was found to be less than that expected from the net area.

7. Construction data show that there is a saving in materials and in time for hollow walls of brick as compared with solid walls.

8. The condition of the horizontal mortar beds in the walls affected the wall strength. Walls in which the beds were smooth were stronger than walls in which the mortar beds were furrowed by from 24 to 109 per cent.

9. Walls laid in cement mortar and kept damp for seven days after construction were not stronger at the age of 60 days than similar walls cured in the laboratory under ordinary conditions.

10. The results of the wallette tests, in which the same variables occurred as in the larger walls, lead in general to the conclusions deduced from the wall tests.

VI. APPENDIX

1. REPORTS ON WORKMANSHIP

It will be observed that no opinions have been offered in the paper as to the grading or classification of the two types of workmanship used. It was made a regular procedure to ask the opinions of such architects, engineers, and contractors who visited the bureau during the progress of this work as to their grading of the workmanship. The opinions expressed were quite variable. The only conclusion warranted was that the workmanship used in different parts of the country varied.

However, in the original program for these tests provision was made for inspection by three different bodies—the American Institute of Architects, the Supervising Architect's Office of the Treasury Department, and the International Bricklayers, Masons and Plasterers' Union.

The American Institute of Architects designated A. L. Harris, municipal architect for the District of Columbia. J. W. Ginder represented the Supervising Architect's Office. No report was received from the International Bricklayers, Masons and Plasterers' Union.

Their reports, in so far as they deal with workmanship, are here reproduced.

(a) COMMENTS BY J. W. GINDER

The physical characteristics of the units employed, the mortar mixtures, the strengths developed, and the technical deductions having been fully covered by others, the following comments are intended to bear only upon the practical aspect of the investigation.

Considering first the manner in which the test units were constructed: Series No. 1 was performed under contract with a mason who also performed the work, so that his every incentive both as a contractor and workman was to complete the work in as short a time as was consistent with obtaining acceptable results. The work was without supervision, except as understood in the preparation of mortar and in the laying up of one wall, so that the mason was free to adopt those methods which appeared to best serve his own interests.

This, it is understood, was one of the purposes of this line of procedure. The resulting work was characterized, as shown by subsequent tests, by furrowing of the mortar beds, the almost complete absence of mortar in the vertical longitudinal joints, and only such mortar in the end joints as was forced in by the "shoving" process of bedding and by depositing the subsequent mortar bed.

All circumstances considered, I believe that this very closely approximates the quality of work generally obtained in commercial construction, where close supervision is not to be expected and the most cogent consideration is economy.

Series No. 2, being built by day labor, exactly the opposite incentive was provided, and it was to the interest of the mason to work deliberately and to prolong the job, in addition to which, it is understood that he was instructed, except in certain instances, to eliminate shoving, that furrowing the beds was prohibited, and that he was to use his best workmanship.

Under these instructions he carefully leveled the beds and slushed all joints full. The subsequent tests showed the wall sections laid up by him to be without voids, and in every way, so far as workmanship was concerned, to be of the highest type for common brickwork.

I believe that such work as of the type which could be expected only under a definite specification, followed by careful supervision, such as would obtain for a high-class public or private structure, where considerations of cost were more or less subordinate.

It should be noted, however, that neither mason was under any restriction as to the thickness of bed to be maintained. I believe that if such a restriction had been imposed, say to a half inch or under, that much of the work performed under series No. 1 might have been of better character with regard to bedding, in that "tapping home" the brick to a reasonably narrow point would have tended to more completely eliminate the furrow in the bed.

As to the curing of the walls, it is noted that no increase in strength was found as a result of damp curing where this was employed, in contrast with those units which were cured in the laboratory under ordinary conditions.

I believe that owing to the saturation of the brick prior to laying and the subsequent protection of the walls from the direct heat of the sun, that all walls were in reality damp cured, the difference being one of degree only, and that if the damp-cured walls were placed in comparison with others laid up under ordinary conditions of outside exposure, a difference in favor of the damp curing might be found.

This theory would seem to be supported to some extent at least by the demonstrated increase in strength of damp-cured mortars over others not so treated.

(b) COMMENTS BY A. L. HARRIS

The walls were laid up in different kinds of mortar and erected by two different mechanics, one of whom laid the bricks to conform with the highest standards of bricklaying, the other laying the bricks according to ordinary every-day methods common to investment building and ordinary commercial work.

The brickwork done by the first mechanic was characterized by deep scoring of the mortar bed with the trowel, buttering a portion of the header only, and the omission of mortar in the center of the walls, except that which is forced into the joints by bedding the brick in the mortar. This gave a very porous or cellular construction to the interior of the wall and was comparable to the kind of brickwork found in ordinary investment and commercial work.

The brickwork done by the second mechanic was characterized by smooth, level bed joints, buttering the entire end of the header and slushing full all vertical interior joints, making a job comparable with what is known as "solid construction."

The class of workmanship in the walls built by the second mechanic (series 2) compares favorably with that obtained by the District of Columbia in its building contracts. The specifications prepared in the municipal architect's office call for all brickwork to be executed with hard-burned red bricks laid in 1 to 3 Portland cement mortar, to which is added hydrated lime not to exceed 15 per cent of the volume of the cement. The brickwork is laid solid throughout, slushing all joints full. The bricks in the interior of the wall are shoved up in a full bed of mortar. This work is inspected by a superintendent of construction, who is constantly on the job during working hours.

WASHINGTON, May 11, 1928.