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COMPRESSIVE STRENGTH OF LARGE BRICK PIERS

BY

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Bureau of Standards

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I. INTRODUCTION

The compressive strength of brick piers has been the subject of several important investigations. Until quite recently, however, testing machines of sufficient capacity had not been available for use in studying the deportment of test specimens comparable in size with those entering into the erection of large structures. A majority of the investigations of the load-bearing value of brick masonry have therefore been conducted on comparatively small specimens. In general, considerable difficulty is experienced in applying laws dedueed from model tests in the laboratory to the problems confronting the engineer in practice. This is especially true of masonry, in which the conditions governing erection vary to a great extent in different districts. The few tests which have been made on large piers were upon specimens of which the conditions pertaining to their erection were ideal, even to the extent that in some cases slightly warped bricks were discarded. Other refinements were introduced, such as special screening of the sand used in the mortar in order to obtain the thinnest possible joints. Such tests are very necessary in the study of certain definite laws. However, due allowance must be made for the conditions under which the tests were conducted, since these conditions are not realized in practice.

In 1914 the technical committee of the National Brick Manufacturers' Association, recognizing the need for a more comprehensive investigation of the strength of brick masonry, outlined a series of tests of large brick piers. These tests have been conducted under a cooperative arrangement between the Bureau of Standards and the National Brick Manufacturers' Association and form the basis of this report. It is believed that the results obtained are of general interest, as the piers tested were of a size commensurate with engineering practice, and the mortars and grade of workmanship applied to their construction were such as would be expected in ordinary building practice. The investigation is composed of tests on piers 2 feet 6 inches square by 10

feet high, in which three grades of brick were used. These bricks were representative of four widely separated districts east of the the Mississippi River. Three mortars were used in the beginning and three bonds, representative of three grades of workmanship, were used throughout the investigation. Transverse, crushing, and absorption tests were made on the individual bricks and a few supplementary pier tests were made, in which wire meshing was used to determine the influence upon the bond.

II. REVIEW OF PREVIOUS TESTS

The following investigations have been carefully considered in the preparation of this report and will be referred to from time to time throughout the discussion.

1. HOWARD'S TESTS[1]

This work consists of several series of pier tests, in which a study was made of various mortars, grades of brick, and methods of laying the bricks. A novel feature of this work was the laying of bricks on edge and in some cases breaking joints every third or sixth course, instead of every course. The piers tested ranged in cross sectional dimensions from 8 inches by 8 inches to 16 inches by 16 inches, the heights varying from 2 feet to 12 feet 6 inches. In these tests, 14 of which were made on face-brick piers laid in 1 part Rosendale cement to 2 parts sand mortar, the strength was found to vary with the height of pier, the ultimate resistance of the pier varying from 12.5 to 18.1 per cent of the compressive strength of the bricks. Thirty-eight common-brick piers of the same mortar and general dimensions developed a strength of from 7.8 to 17.6 per cent of the compressive strength of the bricks. Laying the bricks on edge and breaking joints every third or sixth course increased the strength considerably.

Results of some of these tests are given in the following table, which is taken from Burr's Elasticity and Resistance of the Materials of Engineering, sixth edition, page 426.

[1] "United States report of tests of metals and other materials, 1884–1886," Engineering Record, March 22, 1913; Clay Worker, March, 1913.

TABLE 1.—Crushing Strength of Brick Piers of Various Sizes laid in Different Mortars

No.	Height of pier	Section of pier	Composition of mortar	Weight per cubic foot	Ultimate resistance
	Ft. in.	Inches		Pounds	Lbs./in.²
[a] 1	1 4	8 by 8	1 lime, 3 sand	137.4	2520
[a] 2	6 8	8 by 8	do	133.5	1877
[a] 3	1 4	8 by 8	1 Portland cement, 3 sand	136.3	3776
[a] 4	6 8	8 by 8	do	133.5	2249
[a] 5	2 0	12 by 12	1 lime, 3 sand	.....	1940
[a] 6	2 0	12 by 12	do	.....	1900
[a] 7	10 0	12 by 12	do	131.7	1511
[a] 8	10 0	12 by 12	do	125.0	1807
[a] 9	2 0	12 by 12	1 Portland cement, 2 sand	.....	3670
[a] 10	10 0	12 by 12	do	132.2	2253
[b] 11	1 4	8 by 8	1 lime, 3 sand	135.6	2440
[b] 12	6 8	8 by 8	do	133.6	1540
[b] 13	2 0	12 by 12	do	.....	2150
[b] 14	2 0	12 by 12	do	.....	2050
[b] 15	9 9	12 by 12	do	131.5	1118
[b] 16	10 0	12 by 12	do	136.0	1587
[b] 17	10 0	12 by 12	1 Portland cement, 2 sand	131.0	2003
[b] 18	2 8	16 by 16	do	.....	2720
[b] 19	10 0	16 by 16	do	.....	1887

[a] The kind of brick used in this test was face brick, with an average compressive strength of 13 925 pounds per square inch.

[b] The kind of brick used in this test was common brick, with an average compressive strength of 18 337 pounds per square inch.

2. McCAUSTLAND'S TESTS [2]

This investigation was composed of a series of 14 piers 13 inches by 13 inches in cross sectional dimensions and 80 inches high, which were reinforced laterally in the horizontal joints with steel plates, straps, or wire meshing. The mortar was composed of 1 part Portland cement and 3 parts sand. The bricks used had a compressive strength of 3500 pounds per square inch. In these tests it is shown that the efficiencies of the piers reinforced with iron straps and plates are less than those of the piers without reinforcement. The piers reinforced with wire mesh in every joint developed efficiencies of 46 per cent as compared with 30 per cent for those without reinforcement. However, there is a considerable drop in efficiency from the piers with wire mesh in every joint and piers with wire mesh in every second joint, which developed efficiencies of only 33 per cent.

[2] E. J. McCaustland, Transactions of the Association of Civil Engineering of Cornell University for 1900.

The following table of results of McCaustland's tests is taken from Burr's Elasticity and Resistance of the Materials of Engineering, sixth edition, page 425.

TABLE 2.—Ultimate Compressive Resistance of 13 by 13 by 80 Inch Brick Piers with Metal Reinforcement in Horizontal Joints

[Built with 1:2 Portland cement mortar; joints 0.3 inch thick]

No.	Kind of joints	Ultimate stress		Efficiency per cent of single brick	No.	Kind of joints	Ultimate stress		Efficiency per cent of single brick
		Total	Pounds per square inch				Total	Pounds per square inch	
1	Portland-cement mortar 1:2	194 000	1150	30	7	Wire netting every second course	192 000	1136	33
2	do	200 000	1184		8	do	208 000	1248	
3	Iron straps every fourth course	136 400	810	24	9	Wire netting every course	282 000	1694	46
4	do	155 400	920		10	do	240 000	1440	
5	Iron straps every sixth course	130 000	780	22	11	Iron plate every fourth course	174 000	1030	28
6	Iron straps every eighth course	142 500	843	24	12	do	193 500	1145	
					13	do	162 000	974	
					14	do	143 000	858	

3. MACGREGOR'S TESTS[3]

The object of this investigation was to ascertain what proportions of cement and lime may be used to advantage in a cement-lime mortar and the effect of such mortars on the ultimate compressive strength of brick masonry. Seven sets of brick piers 8 inches by 8 inches by 84 inches were tested. Each set of nine piers represented a different proportion of mortar with varying amounts of hydrated lime. Each set was composed of three groups of three piers each, group 1 being tested at 7 days, group 2 at 28 days, and group 3 at 90 days. The bricks used were hard-burned face bricks. There were also tested seven piers of common brick, one for each different mortar. These piers served as a check on the hard-burned face brick piers, and were tested at the age of 28 days. In these tests piers laid in a mortar composed of 1 part (25 per cent lime and 75 per cent Portland cement) to 3 parts sand by volume developed the highest strength. Piers laid in mortar composed of 1 part (50 per cent lime and 50 per cent Portland cement) to 3 parts sand developed higher strengths than piers laid in 1 part cement to 3 parts sand mortar.

[3] Tests made by Prof. J. S. Macgregor, Columbia University; Bulletin J, Hydrated Lime Bureau of the National Lime Manufacturing Association.

The following data are taken from Bulletin J, Hydrated Lime Bureau of the National Lime Manufacturing Association:

TABLE 3.—Effect of Cement-Lime Mortar on Strength of 8 by 8 Inch Brick Piers

Mortar mixture used		Age when tested	Compressive strength, pounds per square inch	
By volume	By weight		Face-brick piers; each result an average of 3 tests	Common-brick piers; 1 test only
		Days		
1 Portland cement; 3 sand	100 Portland cement; 300 sand	7	2630	.....
		28	2840	1170
		90	2840	.....
0.90 Portland cement; 0.10 hydrated lime; 3 sand.	90 Portland cement; 4 hydrated lime; 300 sand.	7	3080	.....
		28	3170	1189
		90	4435	.....
0.85 Portland cement; 0.15 hydrated lime; 3 sand.	85 Portland cement; 6 hydrated lime; 300 sand.	7	2890	.....
		28	3230	1340
		90	4300	.....
0.75 Portland cement; 0.25 hydrated lime; 3 sand.	75 Portland cement; 10 hydrated lime; 300 sand.	7	3120	.....
		28	3470	1685
		90	4170	.....
0.50 Portland cement; 0.50 hydrated lime; 3 sand.	50 Portland cement; 20 hydrated lime; 300 sand.	7	2760	.....
		28	3100	1300
		90	3820	.....
0.25 Portland cement; 0.75 hydrated lime; 3 sand.	25 Portland cement; 30 hydrated lime; 300 sand.	7	1945	.....
		28	2370	1032
		90	2720	.....
1 hydrated lime; 3 sand	40 hydrated lime; 300 sand	7	1535	.....
		28	1870	.....
		90	1950	.....

4. KREUGER'S TESTS[4]

A recent investigation by Prof. H. Kreuger at the Technical High School in Stockholm, although conducted on small piers, is quite comprehensive in its scope. This investigation includes most of the variables referred to in previous tests and some tests were made to study the effect of eccentric loading. The piers tested were approximately 11 inches square, ranging in height from 6 inches to 33 inches. With bricks of various strengths laid in 1 part lime to 3 parts sand mortar the piers developed strengths of from 18.5 to 26.5 per cent of the ultimate compressive strength of the bricks. It must be noted, however, that the results obtained by Prof. Kreuger are not comparable with results of tests made in the United States, since the method of testing the individual bricks is different. Prof. Kreuger's results were obtained from compression tests on halves of the same brick cemented

[4] Tonind-Ztg. 40, 1916; Clay Worker, July, 1916, and August, 1916.

together. Since the compressive strength developed in this manner would be considerably lower than in the case of a single half brick tested flat, the efficiency of the pier would be correspondingly higher. Tests of the mortars used showed an increase in strength from 28 days to 1 year of 33 to 165 per cent, while the piers increased in strength in the same length of time only 6 to 17 per cent. The introduction of wire mesh in every joint increased the strength 88 to 100 per cent. Piers loaded eccentrically on one-half their bearing surfaces failed at loads slightly under one-half the loads sustained by piers loaded concentrically, and no cracking was observed on the so-called tension side of the pier.

The following data are taken from the Clay Worker for July, 1917, and August, 1917. The results have been converted from the metric to the English units of measure and retabulated.

TABLE 4.—Influence of the Strength of Brick

[Mortar: 1 lime, 3 sand. Age, 28 days]

Number of piers tested	Height of piers	Breadth of piers	Average compressive strength of—		Per cent compressive strength of bricks developed in piers		
			Brick used	Piers	Minimum	Maximum	Average
	Inches	Inches	Lbs./in.²	Lbs./in.²			
5	34.0	10.0	1920	410	19.3	23.7	21.3
4	34.0	9.5	2510	670	23.7	29.5	26.5
3	33.0	9.5	4040	880	20.0	24.3	21.8
5	33.5	9.5	5300	980	15.0	21.2	18.5
4	31.0	9.5	7120	1820	24.7	26.2	25.5
5	30.5	9.0	8600	1680	17.5	21.6	19.5

TABLE 5.—Influence of the Strength of Mortar

[Mortar: 1 lime, 3 sand. Age, 28 days]

Pier No.	Compressive strength of—		Mortar mixture	Compressive strength of piers
	Bricks	Mortar		
	Lbs./in.²	Lbs./in.²		Lbs./in.²
1	4040	0	Dry sand	740
2	4040	38	1 lime; 3 sand	740
3	4040	355	2 lime; 1 cement; 9 sand	1420
4	4040	695	1 lime; 1 cement; 6 sand	1840
5	4040	1280	1 lime; 2 cement; 9 sand	1700
6	4040	1640	2 lime; 1 cement; 7 sand	1930
7	4040	2620	1 cement; 3 sand	1980

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TABLE 6.—Influence of Varying the Height of the Piers

[Mortar: 1 lime, 3 sand]

Pier No.	Compressive strength of bricks	Breadth of pier	Ratio, height to breadth	Compressive strength of piers	Pier No.	Compressive strength of bricks	Breadth of pier	Ratio, height to breadth	Compressive strength of piers
	Lbs./in.²	Inches		Lbs./in.²		Lbs./in.²	Inches		Lbs./in.²
1	3260	10.6	4.3	2340	10	3260	10.6	43.4	880
2	3260	10.6	8.7	2320	11	3260	10.6	48.8	750
3	3260	10.6	13.0	1940	12	3260	10.6	53.2	780
4	3260	10.6	17.4	1620	13	3260	10.6	57.5	640
5	3260	10.6	21.7	1090	14	3260	10.6	61.8	610
6	3260	10.6	26.4	1020	15	3260	10.6	65.8	660
7	3260	10.6	30.7	Broken.	16	3260	10.6	69.7	660
8	3260	10.6	35.4	780	17	3260	10.6	74.5	610
9	3260	10.6	39.5	880	18	3260	10.6	78.8	610

TABLE 7.—Effect of Eccentric Loading

[Mortar: 1 lime, 3 sand]

Height of pier	Breadth of pier	Compressive strength of brick	Compressive strength of mortar	Maximum load	
				Concentric load	Eccentric load
Inches	Inches	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²
33	9.4	4040	50	890	417
33	9.4	5600	50	1220	570
31	9.4	7100	50	1850	850

III. SCOPE OF THE INVESTIGATION

1. PURPOSE

The purpose of this investigation was to determine the strength developed by brick piers of normal size as used in modern buildings, using in their construction such materials and grades of workmanship as are available in the United States.

The data contained in previous studies along this line were in a measure incomplete or represented conditions more favorable than may be realized in practice.

2. OUTLINE OF PROGRAM

The chief variables considered in the original outline of the investigation were (1) the quality of bricks employed with respect to grade and geographical location; (2) the quality and kind of mortar; (3) the grade of workmanship employed; and (4) the bonding of courses or method of laying the bricks.

These were considered the most important variables among the many which enter into an investigation of this nature. The

consideration of minor variables on piers of the size included in the present investigation is not only prohibitive as to cost, but for the most part they may be studied to better advantage on smaller specimens.

The original program included tests of 144 piers. As the work progressed this program was modified to a great extent, as it was found that certain of the variables under consideration did not yield data of sufficient importance to justify the expenditure necessary in the erection and testing of large piers.

(*A*) ORIGINAL PROGRAM.—(*a*) *Districts.*—The bricks were to be selected from four districts east of the Mississippi River, as follows:

Eastern district, A: New York and adjacent territory in New Jersey or eastern Pennsylvania.

Eastern central district, B: Western Pennsylvania and eastern Ohio, comprising Pittsburgh and points within a 50-mile radius.

Western central district, C: Chicago and Galesburg, Ill.

Southern district, D: Atlanta, Birmingham, and New Orleans.

(*b*) *Bricks.*—From each district there were to be selected four grades of brick corresponding with those of Committee C–3, American Society of Testing Materials, tentative specifications 1913. These grades are defined in the following statement:

Class A: Vitrified. Average unit compressive strength at least 5000 pounds per square inch. Average absorption not more than 5 per cent.

Class B: Hard burned. Average unit compressive strength at least 3500 pounds per square inch. Average absorption not more than 12 per cent.

Class C: Common firsts. Average unit compressive strength at least 2000 pounds per square inch. Average absorption not more than 18 per cent.

Class D: Falling below the above specifications.

(*c*) *Mortars.*—Three piers each of three different mortars were to be tested for each grade of bricks used. The following mortars were specified:

A. A pure Portland cement and sand mortar to be composed of 1 part cement to 3 parts sand.

B. A dolomitic lime mortar tempered with Portland cement to be composed of 1 part lime hydrate to 3 parts sand tempered with 5 per cent (dry weight) Portland cement.

C. A lime mortar free of Portland cement to be composed of 1 part lime to 3 parts sand.

(*d*) *Bond and Workmanship.*—Each group of three piers was to be representative of the following three grades of bonding and workmanship:

Grade A: Every other course to be a header course and all joints squeeze joints except inclosures where the joints must be thoroughly filled after the bricks are in place. Each course to be finished complete before beginning the next.

Grade B: Every fourth course to be a header course. Center joints to be filled as thoroughly as practicable without squeezing. Each course to be finished up complete before beginning the next.

Grade C: Every seventh course to be a header course and no squeeze joints used. Outer rim of pier to be built up three or four courses and the center filled in, one course at a time, with loose bricks and slushed with mortar for the bedding of the next course. No individual points to be filled except as they will fill by slushing.

(*B*) Revised Program.—The original program specified a total of 36 piers from each of the four districts, but revisions were made on the basis of results obtained in the early stages of the investigation, which reduced the total number of piers tested from 144 to 50. As the work was begun on materials from the Pittsburgh district and the revisions in the program were based on these tests, the piers of this district more nearly conform to the original program than do those of the other three districts. As a result of the revisions made in the original program, the piers of the Pittsburgh district comprise something over 50 per cent of the entire investigation.

(*a*) *Districts.*—No important changes were made in the matter of districts. It was found to be impracticable, however, to cover the entire field in each district, and with the exception of the Pittsburgh district the bricks obtained from each locality represent the product of a single manufacturer. It is believed, however, that although the geographical locations do not conform in detail with the original program, they are in close enough agreement to be fairly representative of the product east of the Mississippi River.

(*b*) *Bricks.*—The low strengths developed in the piers built of C-grade bricks, as defined in the original program, did not seem to warrant the use of a fourth grade. It was therefore decided to confine the tests to the first three grades only. From the tests of individual bricks selected at random from the materials received at the laboratory, it was found that none of the grades more than

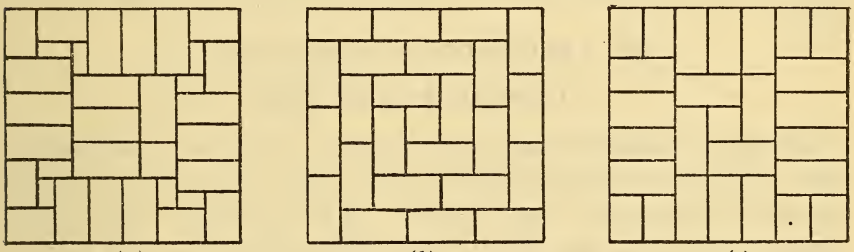
approximated the requirements as outlined in the tentative specification of the American Society for Testing Materials. In one instance where it was necessary to order a second lot of bricks from a manufacturer in district B, the piers of the second lot developed a strength of only one-half those of the first lot. It was decided, therefore, to grade the bricks from each district as follows:

Grade 1: Hard burned or best quality.

Grade 2: Medium burned or considered as common.

Grade 3: Soft burned or poorest product marketed.

In the Chicago district only two grades of brick were obtained, with but a slight difference in the two grades. Only enough material for two piers instead of three was obtained for two of the grades in the New Orleans district. Since the piers from this district were last to be tested it was thought best, after consideration of the trouble experienced in obtaining materials, to finish



(*a*) (*b*) (*c*)

FIG. 1.—*Arrangement of bricks in courses*

the investigation without the two piers needed to complete this district.

(*c*) *Mortars.*—The following mortars were used after consideration of the results obtained on the first few piers of the Pittsburgh district:

Cement mortar: One part pure Portland cement to 3 parts sand.

Lime mortar: One part hydrated lime to 6 parts sand.

Cement-lime mortar: One part composed of 15 per cent hydrated lime (dry weight) and 85 per cent Portland cement (dry weight) to 3 parts sand by weight.

(*d*) *Bond and Workmanship.*—In the case of bond and workmanship no changes were introduced in the method of bonding, the general procedure as outlined in the original program being carried on throughout the investigation. It is believed, however, that the grade of wormanship is somewhat superior to what might be expected in practice. The arrangement of bricks in the header and stretcher courses is shown in Fig. 1.

3. SUPPLEMENTARY TESTS

While no supplementary tests were specified in the original program, numerous tests have been made in order to more closely define the strengths due to the quality of bricks used and the method of laying them in the piers.

(*A*) PIERS.—The results of the earlier tests indicated a falling off in strength as the number of headers were increased. As this is contrary to the accepted theory that the effect of "tying in" the masonry with header courses is to increase the strength, some tests were made to further determine the action of bond. Four piers of the same cross-sectional dimensions as those included in the main investigation and 5 feet in height were built, introducing a different arrangement of the bricks in the header course and the use of wire mesh in the horizontal joints.

(*B*) INDIVIDUAL BRICKS.—Tests of individual bricks were made according to the methods commonly employed in testing laboratories.

IV. LABORATORY PROCEDURE

1. CONSTRUCTION OF PIERS

The piers were built and stored in the laboratory until tested. For convenience in handling they were built on steel base plates 36 inches square by 1 inch thick. As these plates were not removed during the test they were plane surfaced on the side in contact with the testing-machine platen. The plates were carefully leveled on the floor before starting the piers, and the piers were plumbed during erection so that the vertical axis of the finished piers was perpendicular to the plane surface of the steel base plate. The piers were built by contract, and the time necessary to build a single pier varied from one to two days. They were uniformly 10 feet high and the number of courses varied from 41 to 46, depending upon the thickness of the bricks. The horizontal joints varied in thickness from three-eighths to one-half inch.

2. TESTING

(*A*) INDIVIDUAL BRICKS.—No special refinements were introduced in the tests of individual bricks, for it was thought better in view of the practical nature of the investigation to make a more than usual number of tests on each lot of brick in order to obtain a fair average.

(*a*) *Transverse Tests.*—Twenty transverse tests were made on each lot of bricks received, except in the case of grade 3, from

the Pittsburgh district. Of this lot only enough material was available for 10 tests. No bricks were culled because of warpage or cracks due to burning. The tests were made on a small Olsen hand-power machine of 10 000 pounds capacity. Each sample was supported at the ends on round steel bars 1 inch in diameter. These bars were spaced 7 inches, center to center, making a 7-inch span for all tests. Because of the warped condition of certain samples it was necessary in some cases to place fillers between the roller and the brick at one end of the roller. The load was applied at the center of the 7-inch span through a small adjustable hemispherical bearing block resting on a three-fourths-inch diameter round steel rod. From these tests the moduli of rupture were computed by the formula:

$$R = \frac{3\,wl}{2\,bd^2}, \text{ in which}$$

R = modulus of rupture,
w = breaking load,
l = span in inches,
b = breadth in inches,
d = depth in inches.

(*b*) *Compression Tests.*—Of the half bricks left from the transverse tests 10 samples were tested on edge and 10 samples were tested flat. Specimens were selected which had broken through the center in the transverse test, so that the sizes were approximately the same. All samples were capped top and bottom with plaster of Paris, with as nearly as possible uniform thickness of cap. Lack of parallelism of the two bearing surfaces was compensated for in the testing machine by an adjustable hemispherical bearing block.

(*c*) *Absorption Tests.*—Absorption tests were made on the samples to be tested in compression. The samples were first placed in the drying oven and dried to a constant weight, after which they were immersed in water for 48 hours and again weighed. The percentage absorption was then calculated in terms of the dry weight as follows:

$$\text{Per cent absorption} = \frac{w_1 - w}{w}, \text{ in which}$$

w = dry weight,
w_1 = the weight after 48 hours immersion in water.

(*B*) Piers.—(*a*) *Machine Used.*—The piers were tested on the 10 000 000-pound Olsen hydraulic testing machine. This machine

is equipped for compression tests only and is of the vertical type, having a length capacity of 25 feet. The upper platen may be moved up or down on the four pulling screws for adjustment to the length of specimen and is actuated by a 15 horsepower electric motor mounted on top of the platen. The lower platen rests upon a hemispherical base having a 5-foot radius of curvature. The whole rests on a piston 50 inches in diameter, which is actuated by a triple-plunger pump mounted on a tank containing a supply of oil, which is forced into the cylinder under the lower platen. The tank forms the base for a standard Olsen lever system. The pressure in the cylinder is communicated to the lever system through a smaller piston having a knife-edge bearing on the main lever. By this method about one-eightieth of the total load on the machine is weighed. The scale beam, however, is graduated to read direct the total load on the machine. At the capacity of the machine, which is 10 000 000 pounds, the oil pressure in the cylinder is 5 000 pounds per square inch. The machine, exclusive of the pump and lever system, is shown in Fig. 2.

(*b*) *Placing Piers in Machine and Capping.*—The piers were not moved from the position in which they were built until they were aged sufficiently for test. This was four months after building for the lime mortar piers, and one month after building for the cement and cement-lime mortar piers. A steel plate 36 inches square by 1½ inches thick, with suitable eyebolts for crane-hook connection, was placed on top of the pier and connected to the steel base plate by four vertical steel rods. The pier was then moved to the testing machine with an electrical crane and transferred to a smaller auxiliary crane attached to the upper platen of the testing machine. The pier was then lowered gently into place after appropriate centering with the vertical axis of the machine. This was accomplished in all cases without damage to the pier. The upper plate and rods were then removed and the lower platen of the machine was raised so that the combined weight of the pier and platen rested on the oil. The upper platen was then lowered to within a few inches of the pier and the lower platen tipped on its adjustable base until the top of the pier was parallel to the upper platen. Plaster of Paris was then placed on the top of the pier and the upper platen brought down until the superfluous plaster was squeezed out. This left a cap having a uniform thickness of from one-fourth to three-eighths inch.

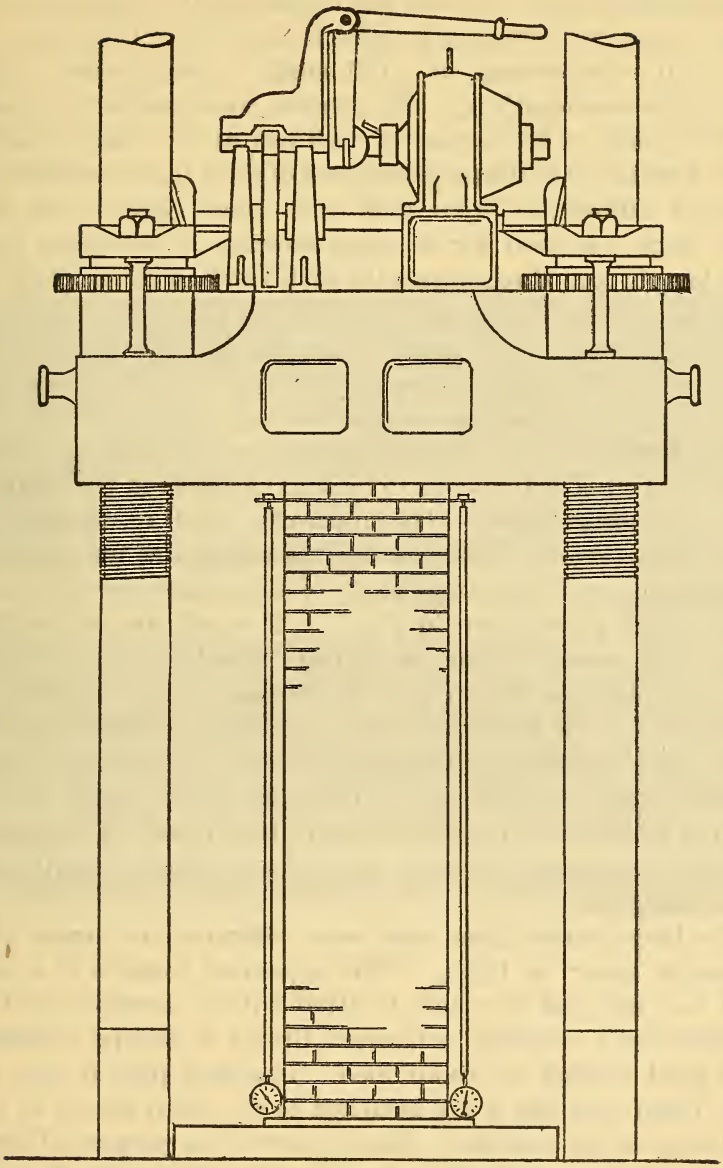


FIG. 2.—*Diagrammatic view of pier in testing machine*

(*c*) *Observations.*—Two sets of observations were made on each pier, one set measuring the total compression from top to bottom courses and the other set measuring the compression and lateral strain in short-gage lengths at the center of the pier. For the total compression or "full-length" compression readings steel plates one-fourth by 1 by 6 inches were inserted in the first and last joints at the corners of each pier at the time of building. Holes were bored in the projecting end of these plates to which were attached adjustable brass rods and Ames gages. The Berry strain gage was used for all measurements of short-gage length. For this purpose three-sixteenths inch German silver plugs were inserted in holes in the brick and set in plaster of Paris. The strain gage points were seated in No. 55 drill holes in the plugs. The holes in the bricks were drilled with a one-half-inch stonecutter's tool, a small air hammer of high speed but very little hitting force. It was found that a slower hammer of greater hitting force had a tendency to loosen the bricks in the mortar.

(*d*) *Instruments Used.*—The apparatus used to measure full-length compression consists of four brass rods, one for each corner of the pier, and four Ames gages of the same type used on the Berry strain gage shown in Fig. 3. The rods are adjustable to length and vertical alignment and are attached by set screws to the steel plates in the top joint of the pier. They are fitted with steel points at the lower end, which are seated in holes bored in the Ames gage spindles. Calibrations of the Ames gages show a possible error of 0.001 inch. The gage length used, however, was 114 inches and in consideration of the amount of compression for each increment of load an error of 0.001 inch is small enough to be negligible.

The Berry strain gage used was calibrated by means of the apparatus shown in Fig. 3. This apparatus consists of a square steel bar, one end of which is fitted with a movable steel plug actuated by a carefully calibrated Brown & Sharpe micrometer gage head reading to 0.0001 inch. The steel plug is very carefully fitted and has a lug attached to it, which moves in a slot in the top of the steel bar. The lug serves the purpose of keeping the plug in the same relative position for each series of readings and also furnishing the surface in which are bored the drill holes for the movable leg of the strain gage. The following three sizes of holes are bored in the lug; No. 54 diameter, 0.055 inch; No. 55 diameter, 0.052 inch; No. 56 diameter, 0.046 inch. Drill

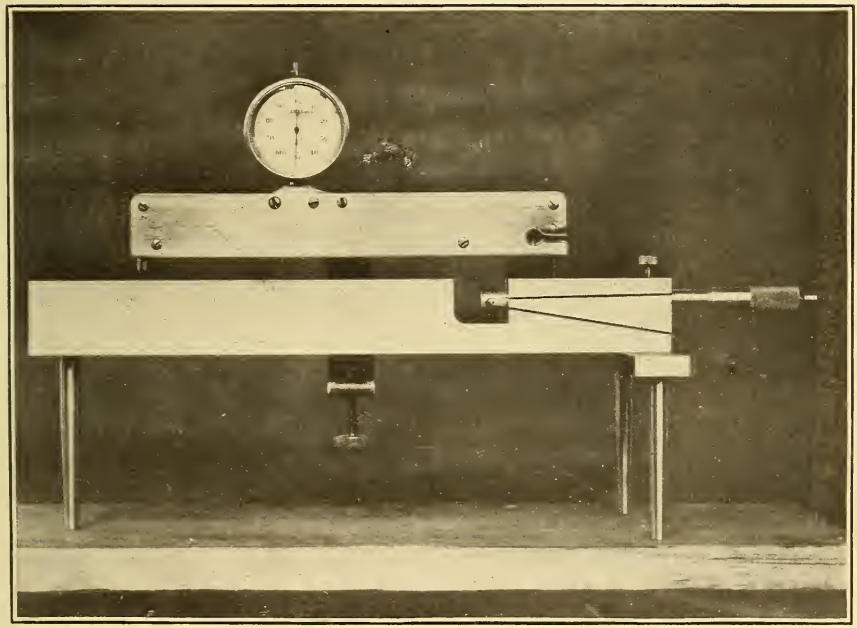


FIG. 3.—*Apparatus for calibrating Berry strain gage showing gage in position for calibration*

holes are placed in the main part of the square bar at proper distances from the lug so that Berry gages from 2 to 10 inch gage lengths may be calibrated. An error is introduced in the Berry gage readings, due to the seating of the movable leg in the drill holes. The effect is the same as would be produced by shortening the movable leg of the gage and changes the multiplying ratio so that a different correction constant must be used for each size of drill hole. To determine this constant with the apparatus shown in Fig. 3 requires very little time, and no special

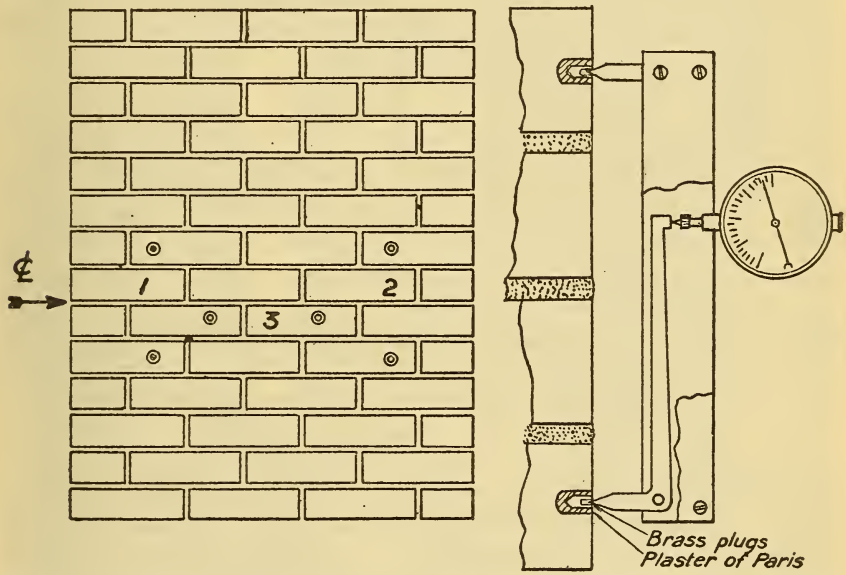


FIG. 4.—*Showing location of Berry strain gage stations on each face of pier and method of seating gage points*

care need be exercised regarding changes of temperature. A sketch showing the locations of the Berry gage observation stations, the method of inserting the plugs, and the position of the gage is shown in Fig. 4.

V. RESULTS OF TESTS

1. OBSERVED DATA

In view of the large mass of data contained in the original log sheets, the data have been grouped in tables, and only in those cases which are characteristic of types will the original logs be presented. The data obtained are summarized in Tables 8 and 9. These tables include details of construction, age, ultimate

stress, and modulus of elasticity for each pier, also the average strengths and percentage of absorption of the bricks used in their construction. The strengths of bricks and piers included in Table 8 are shown in Fig. 5. The lines connecting the points in this diagram indicate how the strength of the piers follow the strengths of the individual bricks. Table 10 is a copy of

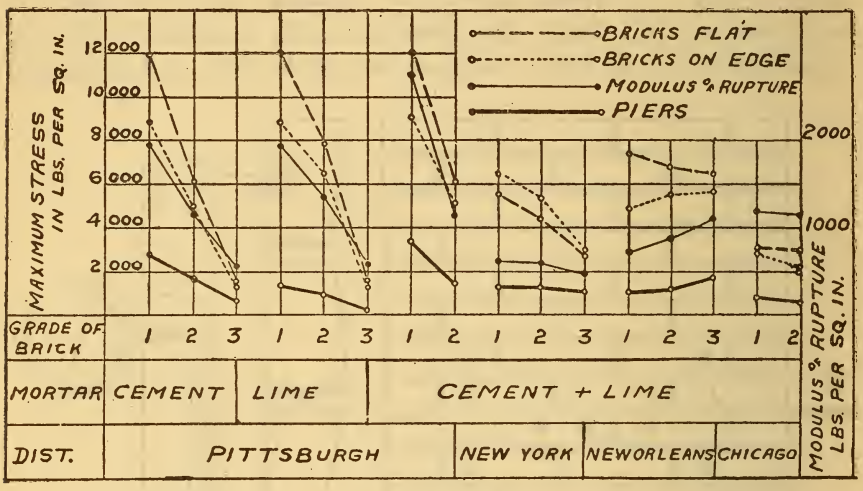


FIG. 5.—*Strength of piers and individual bricks shown diagrammatically*

See Table 1 for exact values

the original log for pier B 30, which is typical of the entire investigation. In Table 11 is shown the log of grade 1 bricks from the Pittsburgh district. Photographs of piers after failure are shown in Figs. 6 to 14. In these photographs is shown the type of failure characteristic of all piers tested, the vertical cracking of the masonry being very pronounced in all cases.

FIG. 6.—*Pier B 14, Serial No. 2. Grade 1 bricks from Pittsburgh district laid in cement mortar*

FIG. 7.—*Pier B 31, Serial No. 10. Grade 1 bricks from Pittsburgh district laid in cement lime mortar*

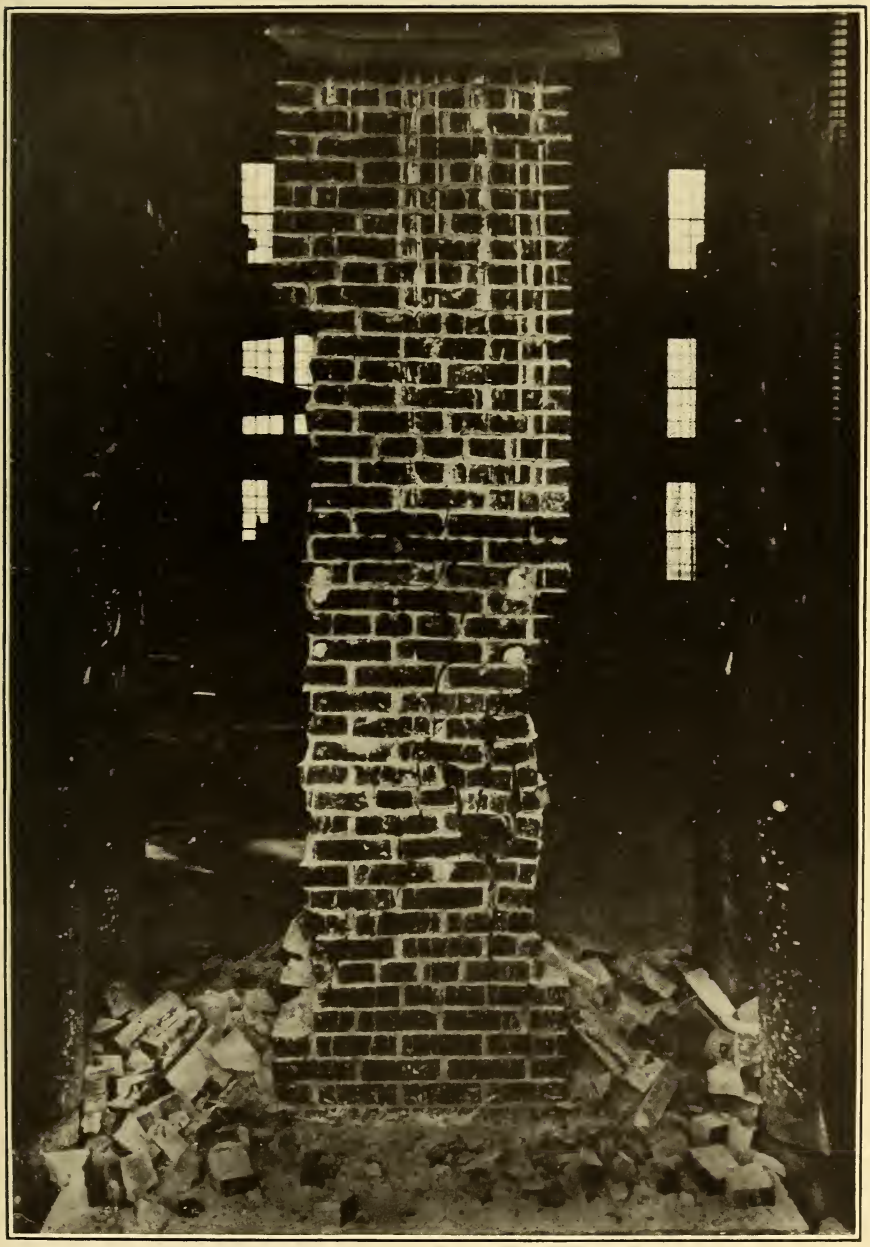


FIG. 8.—*Pier B 9, Serial No. 18. Grade 1 bricks from Pittsburgh district laid in lime mortar*

FIG. 9.—*Pier B 28, Serial No. 14. Grade 2 bricks from Pittsburgh district laid in cement lime mortar*

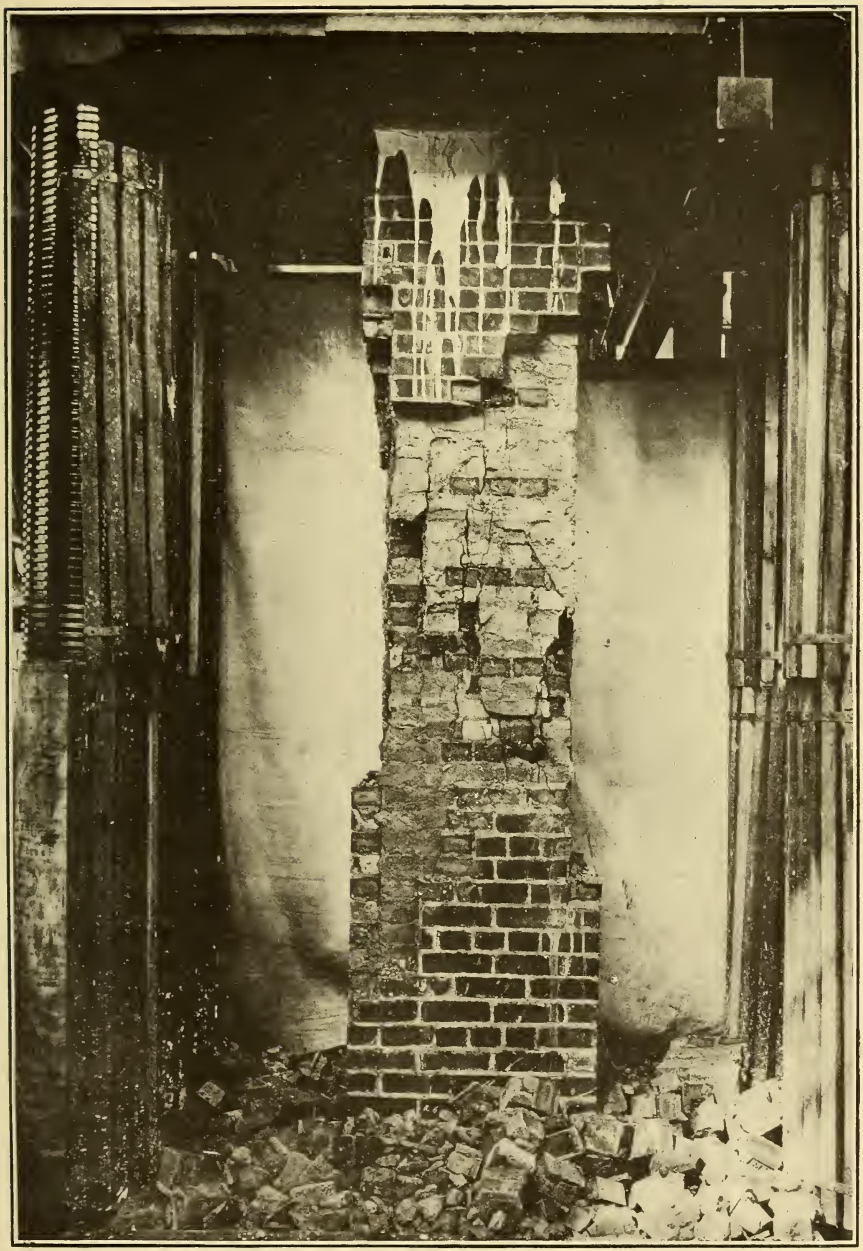


FIG. 10.—*Pier B 42, Serial No. 39. Grade 3 bricks from New York district laid in cement lime mortar*

FIG. 11.—*Pier B 47, Serial No. 25. Grade 1 bricks from New Orleans district laid in cement lime mortar*

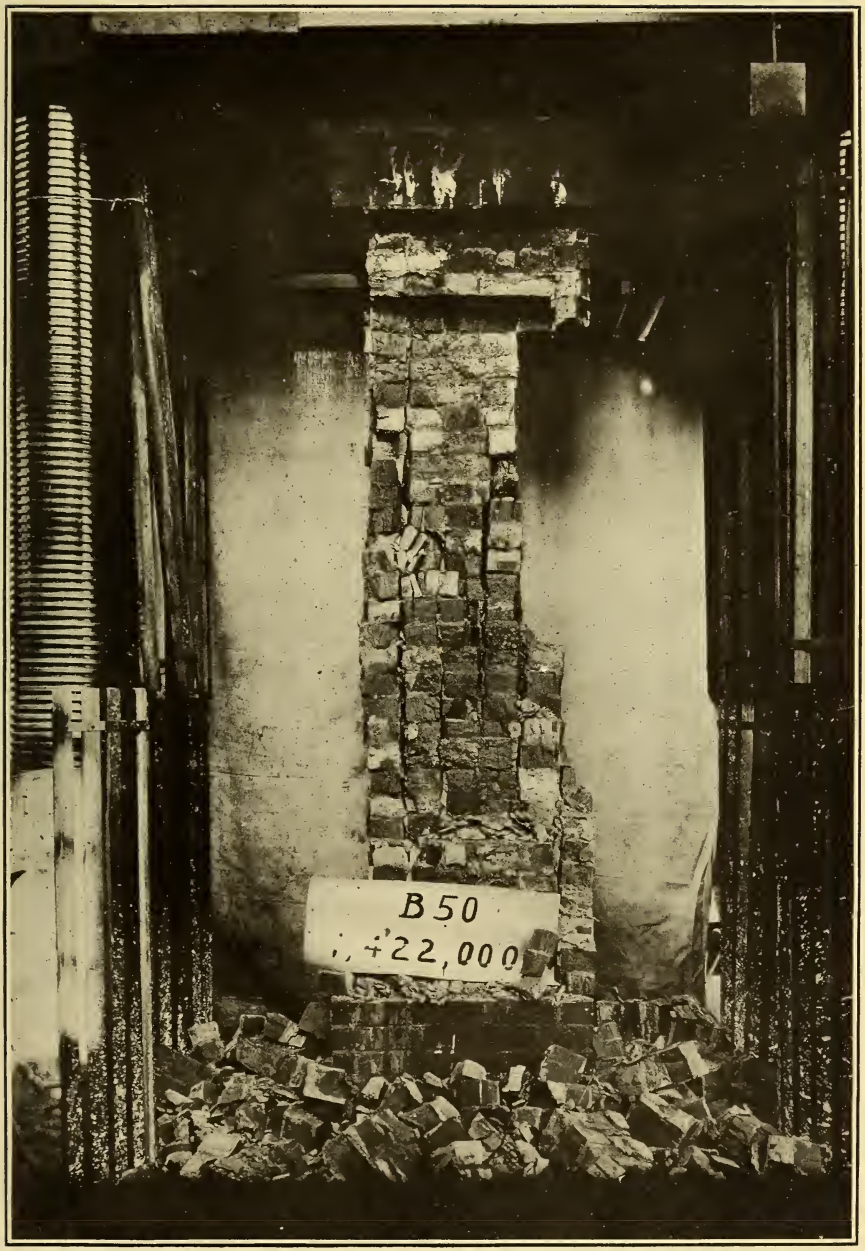


FIG. 12.—*Pier B 50, Serial No. 30. Grade 3 bricks from New Orleans district laid in cement lime mortar.*

FIG. 13.—*Pier B 35, Serial No. 41. Grade 1 bricks from Chicago district laid in cement lime mortar*

TABLE 8.—Details of Construction and Summary of Test Data. (Piers of Main Investigation)

Serial number	Piers: Construction data: Mark on pier	District	Grade of bricks	Bond: Header and stretcher	Courses	Mortar	Height in feet	Piers: Test data: Age in days	Area in square inches	Maximum load in pounds	Maximum load in pounds per square inch	Modulus of elasticity	Bricks: Test data: Average compressive strength, flat	Average compressive strength on edge	Average transverse strength, modulus of rupture	Per cent absorption
PITTSBURGH DISTRICT, CEMENT MORTAR																
1	B13	B	1	1:1	46	1 cement; 3 sand...	10	30	930	2 520 000	2710	2 500 000	11 990	8900	1945	4.08
2	B14	B	1	1:3	46	.....do.....	10	30	930	2 550 000	2740	3 200 000	11 990	8900	1945	4.08
3	B15	B	1	1:6	46	.....do.....	10	30	930	2 697 000	2900	3 200 000	11 990	8900	1945	4.08
4	B17	B	2	1:1	45	.....do.....	10	32	856	1 714 000	2000	2 250 000	7880	6450	1370	7.46
5	B18	B	2	1:3	45	.....do.....	10	32	885	1 834 000	2070	2 000 000	7880	6450	1370	7.46
6	B27	B	2	1:6	44	.....do.....	10	33	946	824 000	870	833 000	2450	2040	675	15.16
7	B1	B	3	1:1	41	.....do.....	10	29	1024	524 000	510	700 000	1659	1350	345	16.28
8	B2	B	3	1:3	41	.....do.....	10	29	1043	580 000	560	733 000	1659	1350	345	16.28
9	B3	B	3	1:6	41	.....do.....	10	32	1024	660 000	650	533 000	1659	1350	345	16.28
PITTSBURGH DISTRICT, CEMENT AND LIME MORTAR																
10	B31	B	1	1:1	45	1 (15 per cent lime, 85 per cent cement); 3 sand.	10	90	841	3 211 000	3800	3 500 000	11 965	10 050	2775	1.28
11	B29	B	1	1:3	45	.....do.....	10	90	841	2 714 000	3220	3 050 000	11 965	10 050	2775	1.28
12	B30	B	1	1:6	45	.....do.....	10	90	841	2 787 000	3300	3 500 000	11 965	10 050	2775	1.28
13	B20	B	2	1:1	45	.....do.....	10	33	908	1 594 000	1760	1 550 000	7880	6450	1370	7.46
14	B28	B	2	1:3	44	.....do.....	10	32	961	838 000	870	750 000	2450	2040	675	15.16
15	B22	B	2	1:6	45	.....do.....	10	30	878	1 545 800	1760	1 625 000	7880	6450	1370	7.46

TABLE 8.—Details of Construction and Summary of Test Data. (Piers of Main Investigation)—Continued

PITTSBURGH DISTRICT, LIME MORTAR

Serial number	Piers												Bricks: Test data			
	Construction data							Test data								
	Mark on pier	District	Grade of bricks	Bond: Header and stretcher	Courses	Mortar	Height in feet	Age in days	Area in square inches	Maximum load in pounds	Maximum load in pounds per square inch	Modulus of elasticity	Average compressive strength, flat	Average compressive strength on edge	Average transverse strength, modulus of rupture	Per cent absorption
16	B7	B	1	1:1	45	1 lime; 6 sand.....	10	120	940	1 360 000	1450	725 000	11 990	8900	1945	4.08
17	B8	B	1	1:3	45	.....do.....	10	120	940	1 197 500	1270	416 700	11 990	8900	1945	4.08
18	B9	B	1	1:6	45	.....do.....	10	120	940	1 280 000	1360	750 000	11 990	8900	1945	4.08
19	B10	B	2	1:1	44	.....do.....	10	120	906	764 000	840	620 000	7880	6450	1370	7.46
20	B11	B	2	1:3	44	.....do.....	10	120	906	804 000	890	687 000	7880	6450	1370	7.46
21	B12	B	2	1:6	44	.....do.....	10	120	900	892 000	990	620 000	7880	6450	1370	7.46
22	B4	B	3	1:1	41	1 lime; 3 sand.....	10	120	1024	215 500	210	300 000	1659	1350	345	16.28
23	B5	B	3	1:3	41	.....do.....	10	120	1024	182 000	178	300 000	1659	1350	345	16.28
24	B6	B	3	1:6	41	.....do.....	10	120	1024	129 000	126	270 000	1659	1350	345	16.28
NEW ORLEANS DISTRICT, CEMENT AND LIME MORTAR																
25	B47	D	1	1:1	41	1 (15 per cent lime, 85 per cent cement); 3 sand.	10	29	841	1 223 000	1450	1 533 000	7340	4910	733	16.80
26	B48	D	1	1:3	41	.....do.....	10	29	841	1 475 000	1760	1 533 000	7340	4910	733	16.80
27	B52	D	2	1:1	41	.....do.....	10	31	841	1 370 000	1630	1 563 000	6880	5490	893	16.40
28	B53	D	2	1:3	41	.....do.....	10	30	841	1 506 000	1790	1 750 000	6880	5490	893	16.40
29	B49	D	3	1:1	41	.....do.....	10	30	841	1 580 000	1880	1 833 000	6510	5700	1090	17.10
30	B50	D	3	1:3	41	.....do.....	10	29	841	1 422 000	1690	1 583 000	6510	5700	1090	17.10
31	B51	D	3	1:6	41	.....do.....	10	31	841	1 397 000	1660	1 583 000	6510	5700	1090	17.10

NEW YORK DISTRICT, CEMENT AND LIME MORTAR

32	B44	A	1	1:1	45	1 (15 per cent lime, 85 per cent cement); 3 sand.	10	32	791	921 500	1170	875 000	5630	6440	601	16.40
33	B45	A	1	1:3	45	.....do.....	10	32	791	1 033 500	1300	875 000	5630	6440	601	16.40
34	B46	A	1	1:6	45	.....do.....	10	31	791	998 000	1260	875 000	5630	6440	601	16.40
35	B38	A	2	1:1	45	.....do.....	10	30	784	1 001 000	1280	875 000	4430	5449	616	18.60
36	B39	A	2	1:3	45	.....do.....	10	31	791	1 011 000	1280	1 125 000	4430	5449	616	18.60
37	B40	A	2	1:6	45	.....do.....	10	31	791	967 500	1220	817 000	4430	5449	616	18.60
38	B41	A	3	1:1	45	.....do.....	10	31	791	840 500	1070	484 000	2710	2970	497	19.30
39	B42	A	3	1:3	45	.....do.....	10	31	791	840 000	1060	667 000	2710	2970	497	19.30
40	B43	A	3	1:6	45	.....do.....	10	30	791	808 000	1020	600 000	2710	2970	497	19.30

CHICAGO DISTRICT, CEMENT AND LIME MORTAR

41	B35	C	1	1:1	46	1 (15 per cent lime, 85 per cent cement); 3 sand.	10	32	841	706 700	840	833 000	3200	3010	1180	16.20
42	B36	C	1	1:3	46	.....do.....	10	29	812	641 500	790	750 000	3200	3010	1180	16.20
43	B37	C	1	1:6	46	.....do.....	10	30	812	660 500	810	750 000	3200	3010	1180	16.20
44	B32	C	2	1:1	46	.....do.....	10	30	812	606 500	750	833 000	3150	2710	1140	16.20
45	B33	C	2	1:3	46	.....do.....	10	30	812	572 000	700	650 000	3150	2710	1140	16.20
46	B34	C	2	1:6	46	.....do.....	10	30	812	578 500	710	580 000	3150	2710	1140	16.20

TABLE 9.—Details of Construction and Summary of Test Data. (Supplementary Piers)

Serial number	Piers											Bricks: Test data			
	Construction data						Test data								
	Mark on pier	District	Grade of brick	Type of bond	Mortar	Height in feet	Age in days	Area in square inches	Maximum load in pounds	Maximum load in pounds per square inch	Per cent increase or decrease in strength	Average compressive strength, flat	Average compressive strength on edge	Average transverse strength, modulus of rupture	Per cent absorption
47	B23	B	2	1 header, type (*a*), Fig. 1, to 1 stretcher.	1 (15 per cent lime, 85 per cent cement); to 3 sand.	5	30	915	1 580 000	1730	0	2450	2040	675	15.16
48	B24	B	2	1 header, type (*c*), Fig. 1, to 1 stretcher.	.....do.....	5	30	915	1 678 000	1840	+6.4	2450	2040	675	15.16
49	B25	B	2	Same as No. 47, with 18 gage No. 2 galvanized-iron wire mesh in every joint.	.....do.....	5	30	924	2 100 000	2270	+31.2	2450	2040	675	15.16
50	B26	B	2	Same as No. 47, with 18 gage No. 2 galvanized-iron wire mesh in every fourth joint.	.....do.....	5	30	930	1 364 000	1470	−15.0	2450	2040	675	15.19

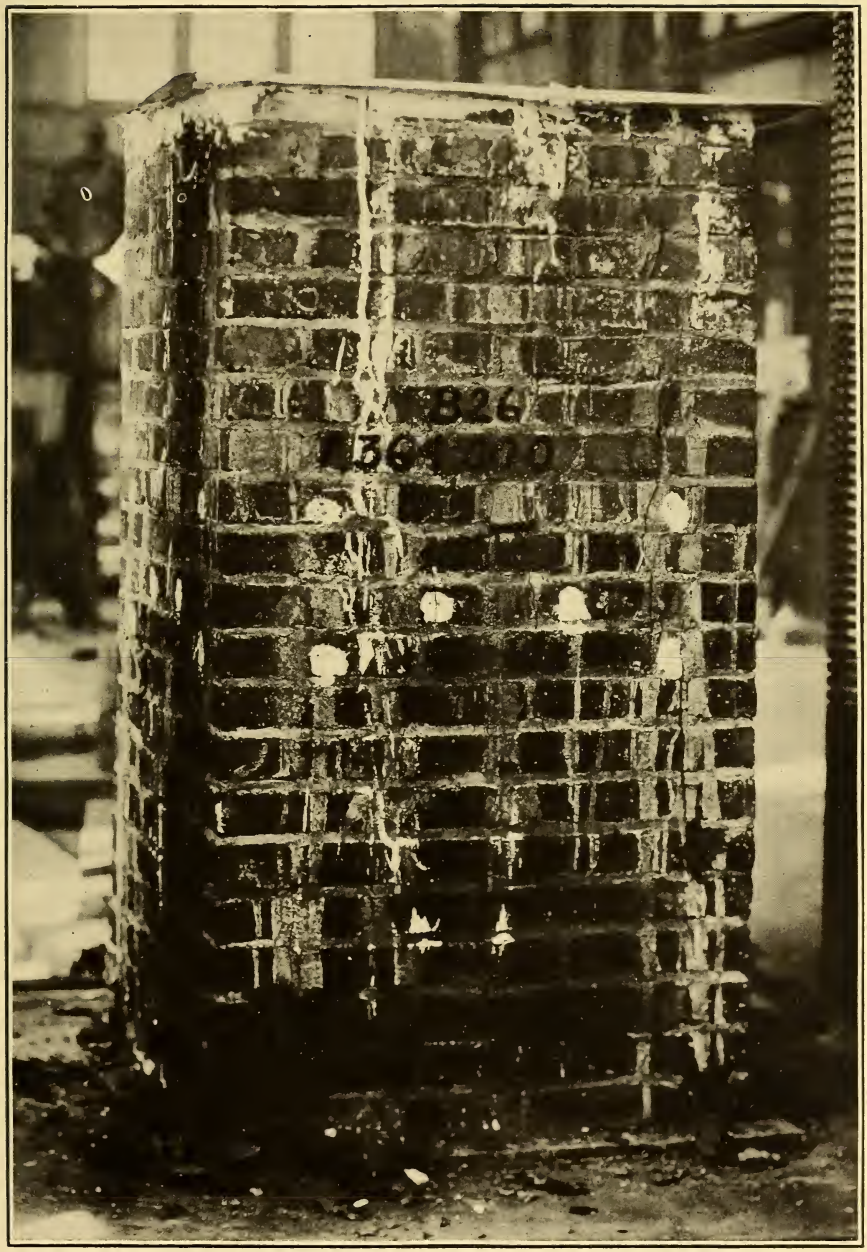


FIG. 14.—*Pier B 26, Serial No. 50. Grade 2 bricks from Pittsburgh district laid in cement lime mortar. Reinforced in every fourth horizontal joint with wire mesh*

TABLE 10.—Representative Test Log of Single Pier. (Pier B 30, Serial No. 12) [a]

Applied load		Readings on north face			Readings on west face		
Pounds per square inch	Pounds	1	2	3	1	2	3
50	42 050	0.0340	0.0260	0.0280	0.0266	0.0292	0.0260
200	168 200	.0344	.0266	.0280	.0274	.0292	.0260
400	336 400	.0350	.0271	.0280	.0282	.0296	.0260
600	504 600	.0354	.0276	.0280	.0284	.0306	.0260
800	672 800	.0361	.0280	.0278	.0290	.0308	.0260
1000	841 000	.0366	.0284	.0278	.0296	.0313	.0258
1400	1 177 400	.0378	.0294	.0276	.0308	.0328	.0258
1800	1 513 800	.0391	.0306	.0273	.0323	.0340	.0256
2200	1 850 200	.0406	.0318	.0268	.0343	.0358	.0250
2600	2 186 000	.0426	.0332	.0265	.0364	.0380	.0244

Applied load		Readings on south face			Readings on east face		
Pounds per square inch	Pounds	1	2	3	1	2	3
50	42 050	0.0351	0.0318	0.0282	0.0270	0.0338	0.0343
200	168 200	.0350	.0318	.0284	0270	.0341	.0343
400	336 400	.0358	.0322	.0283	.0276	.0346	.0342
600	504 600	.0362	.0328	.0282	.0282	.0252	.0341
800	672 800	.0367	.0333	.0280	.0286	.0357	.0340
1000	841 000	.0373	.0338	.0279	.0292	.0362	.0340
1400	1 177 400	.0383	.0348	.0278	.0302	.0374	.0338
1800	1 513 800	.0394	.0358	.0276	.0309	.0384	.0334
2200	1 850 200	.0307	.0370	.0274	.0320	.0396	.0330
2600	2 186 000	.0325	.0386	.0272	.0336	.0409	.0324

Applied load		Extensometer rod readings			
Pounds per square inch	Pounds	7 northeast	8 northwest	9 southwest	10 southeast
50	42 050	0.0000	0.0000	0.0000	0.0000
200	168 200	.0045	.0088	.0027	.0003
400	336 400	.0107	.0165	.0080	.0065
600	504 600	.0193	.0244	.0140	.0133
800	672 800	.0260	.0312	.0202	.0207
1000	841 000	.0337	.0381	.0263	.0278
1200	1 009 200	.0408	.0460	.0333	.0352
1400	1 177 400	.0480	.0541	.0403	.0420
1600	1 345 600	.0550	.0634	.0478	.0479
1800	1 513 800	.0621	.0729	.0550	.0540
2000	1 682 000	.0703	.0852	.0638	.0603
2200	1 850 200	.0791	.0973	.0731	.0696
2400	2 018 400	.0897	.1086	.0850	.0800
2600	2 186 600	.0905	.1149	.0953	.0900
2800	2 354 800	.0978	.1250	.1083	.1027
3000	2 523 000	.0885	.1265	.1119	.1170
	2 787 000	(b)	.....	.....	.....

[a] Dimensions of pier, 29 by 29 inches by 10 feet ⅛ inch; bricks, grade 1, District B; number of courses, 45; bond, 1 header, 6 stretchers; mortar, 1 (15 per cent lime and 85 per cent cement) to 3 sand; good bearing was obtained over the entire area; pier failed uniformly on all faces; gage length extensometer rods, 114 inches; Berry gage length, 8 inches.

[b] Maximum load.

TABLE 11.—Representative Test Log of Single Lot of Individual Bricks. (Grade 1 Bricks from District B)

Transverse tests					Transverse tests				
Span in inches l	Width in inches b	Depth in inches d	Load in pounds W	Modulus of rupture $\frac{3\,Wl}{2\,bd^2}$	Span in inches l	Width in inches b	Depth in inches d	Load in pounds W	Modulus of rupture $\frac{3\,Wl}{2\,bd^2}$
7	3.85	2.30	6300	3250	7	3.85	2.30	3910	2020
7	3.90	2.30	4490	2290	7	3.85	2.30	5300	2740
7	3.85	2.30	5850	3020	7	3.90	2.30	4870	2480
7	3.85	2.30	5800	3000	7	3.90	2.30	5400	2760
7	3.85	2.30	4740	2440	7	3.90	2.30	5360	2740
7	3.85	2.30	5730	2960	7	3.90	2.30	4630	2360
7	3.90	2.30	5870	3000	7	3.90	2.30	5050	2580
7	3.90	2.30	5920	3020	7	3.90	2.30	7230	3690
7	3.90	2.30	5950	3030	7	3.90	2.30	5230	2670
7	3.90	2.30	6075	3100	7	3.90	2.30	4660	2380
					Av.....	.....	.....	.....	2775

No.	Absorption tests			Half brick flat			Half brick on edge		
	Dry weight in kilograms	Wet weight in kilograms	Per cent absorption	Dimensions in inches	Load in pounds	Load in pounds per square inch	Dimensions in inches	Load in pounds	Load in pounds per square inch
1	2.876	2.940	2.23	3.6 by 4.3	172 300	11 100	2.3 by 4.2	83 600	8330
2	2.925	2.945	.68	3.9 by 4.2	201 000	12 250	2.3 by 4.3	111 200	11 250
3	2.845	2.866	.74	3.9 by 3.75	180 500	12 350	2.3 by 4.1	103 400	10 900
4	2.845	2.881	1.26	3.9 by 4.0	201 500	12 750	2.3 by 4.3	92 900	9300
5	2.863	2.878	.53	3.9 by 4.15	175 400	10 830	2.3 by 4.2	124 800	12 400
6	2.842	2.864	.77	3.9 by 4.3	219 100	13 050	2.3 by 4.15	79 500	8330
7	2.932	2.975	1.47	3.9 by 4.3	186 000	11 100	2.3 by 4.2	84 300	8720
8	2.866	2.909	1.50	3.9 by 4.2	198 400	12 100	2.3 by 4.25	106 000	10 830
9	2.815	2.874	2.09	3.9 by 4.1	186 400	11 650	2.3 by 3.95	69 000	7600
10	2.885	2.937	1.80	3.9 by 4.05	161 700	10 200	2.3 by 4.4	82 700	8180
11	2.854	2.870	.56	3 9 by 3.9	210 200	13 850	2.3 by 4 25	97 000	9920
12	2.920	2.970	1.71	3.9 by 4.4	211 800	12 350	2.3 by 4.05	138 500	14 870
Av.	.....	.....	1.28	.....	.....	11 965	.....	.....	10 050

2. DERIVED DATA

(A) Relation of Transverse Strength of Bricks to Compressive Strength of Piers.—For the most part, efforts to establish ..... relations between the compressive strength of the bricks and the ultimate strength of the piers have met with small success except in cases previously referred to where the conditions pertaining to the erection of the test piers were ideal. Observations recorded in the first few tests of the present investi-

gation pointed to certain characteristics of failure indicating that the transverse strength of the bricks might bear a close relation to the ultimate strength of the piers. For this reason the tranverse strength was determined on each lot of bricks and the

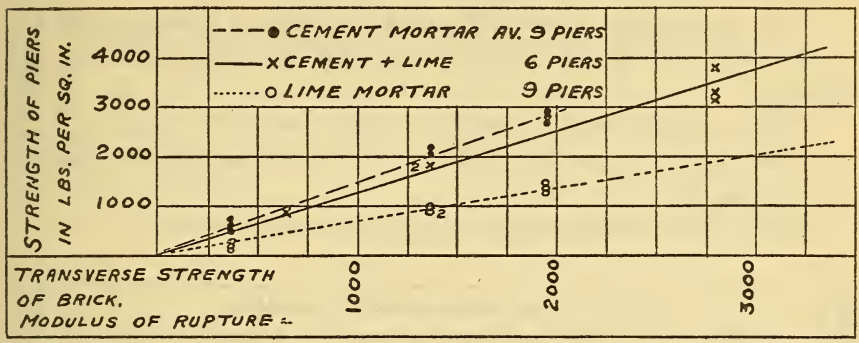


FIG. 15.—*Showing relation of transverse strength of individual bricks to compressive strength of piers, representing three grades of brick and three mortars from Pittsburgh district*

average unit transverse strength or modulus of rupture obtained. These averages have been plotted as abscissas and the unit loads sustained by the piers as ordinates and are shown in Figs. 15 and 16. Fig. 15 includes only piers of the Pittsburgh district repre-

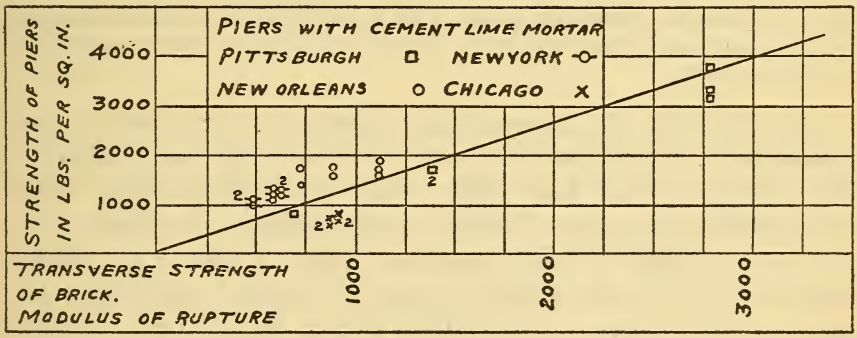


FIG. 16.—*Showing relation of transverse strength of individual bricks to compressive strength of piers, representing three grades of brick from four districts. All piers laid in cement-lime mortar*

senting three grades of mortars, while Fig. 16 includes piers from all districts laid in cement-lime mortar. In both cases it is shown that the transverse strength of the bricks is proportional to the compressive strength of the piers. For use in computing the

strength of brick piers the empirical formula $P = K\ R$ is derived from these plots. In this formula

$P =$ the compressive strength of the pier in pounds per sq. in.,

$R =$ the modulus of rupture of the bricks,

K is a constant depending upon the kind of mortar used.

The values of K for mortars included in these tests are as follows:

For 1 part Portland cement to 3 parts sand, $K = 1.45$,

For 1 part (15 per cent lime 85 per cent cement) to 3 parts sand, $K = 1.25$,

For 1 part hydrated lime to 6 parts sand, $K = 0.65$.

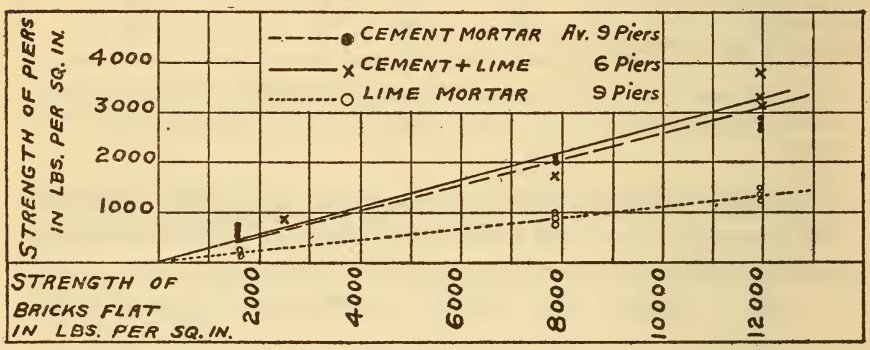


Fig. 17.—*Relation of compressive strength of single bricks (flat) to compressive strength of piers, representing three grades of brick from four districts. All bricks laid in cement-lime mortar*

(B) Relation of Compressive Strength of Bricks to Compressive Strength of Piers.—The average unit compressive strength of the half bricks tested flat and on edge have been plotted in the same manner as the modulus of rupture and are shown in Figs. 17 to 20, inclusive. Figs. 17 and 19 are representative of the three different grades of mortar, while Figs. 18 and 20 include piers of all districts laid in cement-lime mortar. In these plots it is shown that the compressive strengths of the bricks is proportional to the ultimate compressive strength of the piers and the formula

$P = K\ p$ is derived, in which

$P =$ the unit compressive strength of the pier,

$p =$ the unit compressive strength of the bricks,

K is a constant, depending upon the grade of mortar.

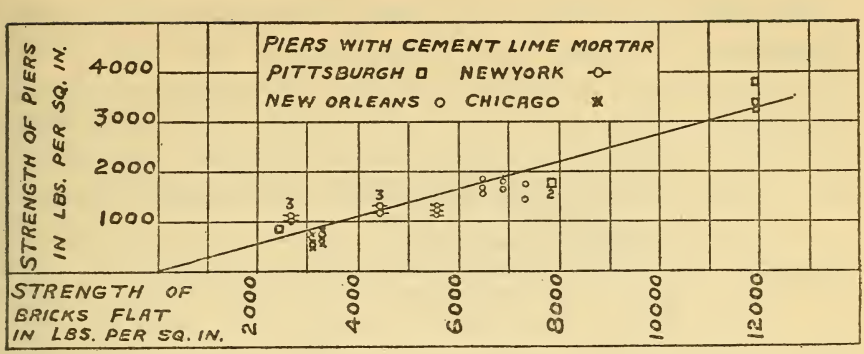


FIG. 18.—*Relation of compressive strength of single bricks (flat) to compressive strength of piers, representing three grades of brick and three mortars from Pittsburgh district*

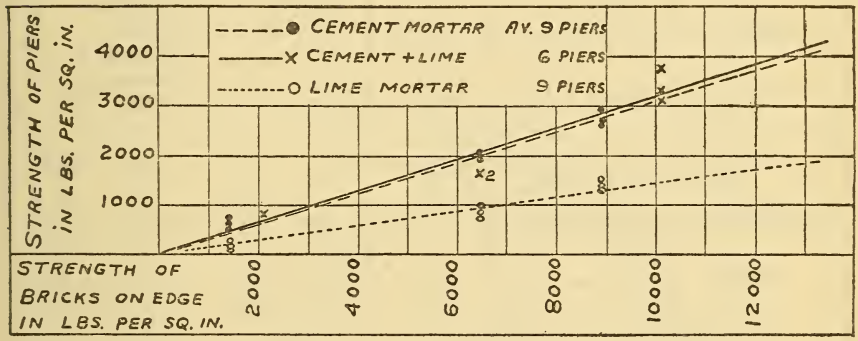


FIG. 19.—*Relation of compressive strength of single bricks (on edge) to compressive strength of piers, representing three grades of brick and three mortars from Pittsburgh district*

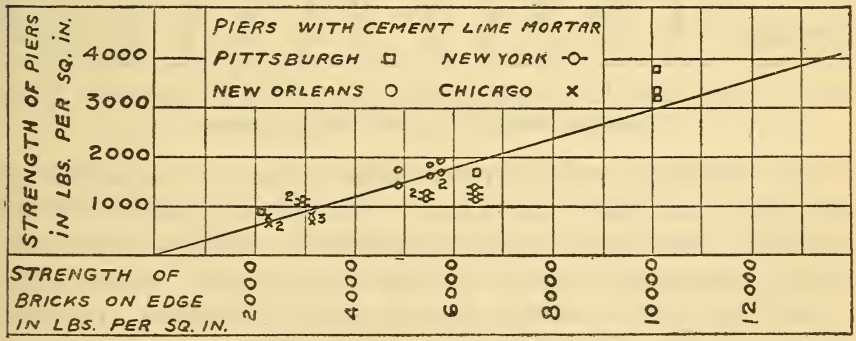


FIG. 20.—*Relation of compressive strength of single bricks (on edge) to compressive strength of piers, representing three grades of brick from four districts. All piers laid in cement-lime mortar*

The following table gives the value of K for the grade of mortar employed:

Bricks tested	Mortar	Value of K
Flat	1 cement to 3 sand by weight	0.27
	1 (15 per cent lime, 85 per cent cement) to 3 sand by weight	.26
	1 lime hydrate to 6 sand by weight	.11
On edge	1 cement to 3 sand by weight	.32
	1 (15 per cent lime, 85 per cent cement) to 3 sand by weight	.30
	1 lime hydrate to 6 sand weight	.14

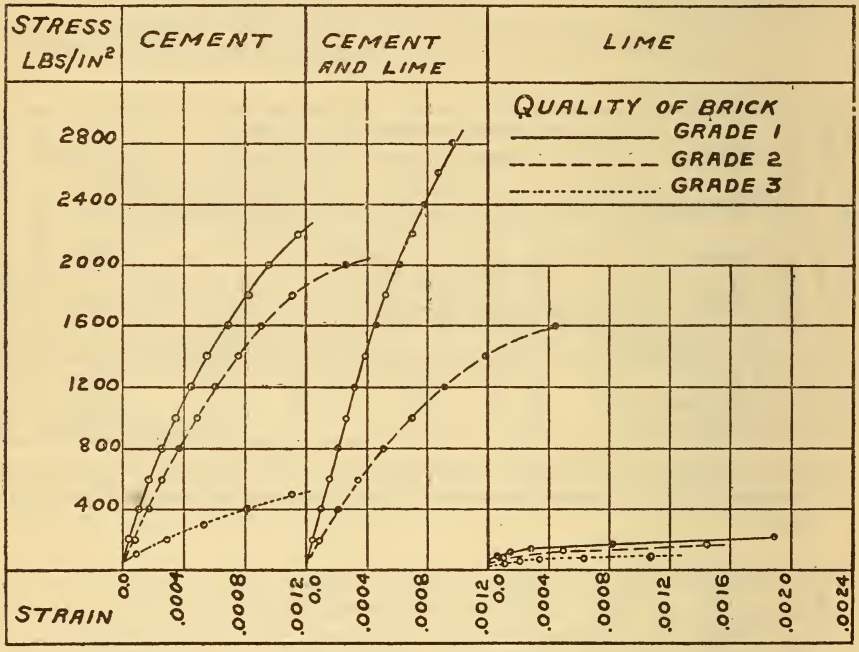


FIG. 21.—*Stress strain curves showing relative degree of compressibility of the various grades of brick laid in different kinds of mortar*

(C) MODULUS OF ELASTICITY.—The modulus of elasticity of the piers has been determined from the stress-strain curves obtained from the full-length compression readings. Representative stress-strain curves are shown in Fig. 21. This figure shows the relative stiffness of piers built of different grades of bricks and mortars. There is very little difference in the modulus of elasticity for piers of cement mortar and those of cement-lime mortar in which bricks of the same grade were used. There is a big difference, however, in the modulus of piers of these mortars and those of pure lime mortar. It may also be seen that

in the case of cement and cement-lime mortars, the piers of low-grade bricks have a considerably lower modulus than those of the higher grades, while very little difference is apparent in the case of pure lime mortar. In Fig. 22 it is shown that in the cement and cement-line mortar piers the modulus of elasticity is proportional to the compressive strength of the pier.

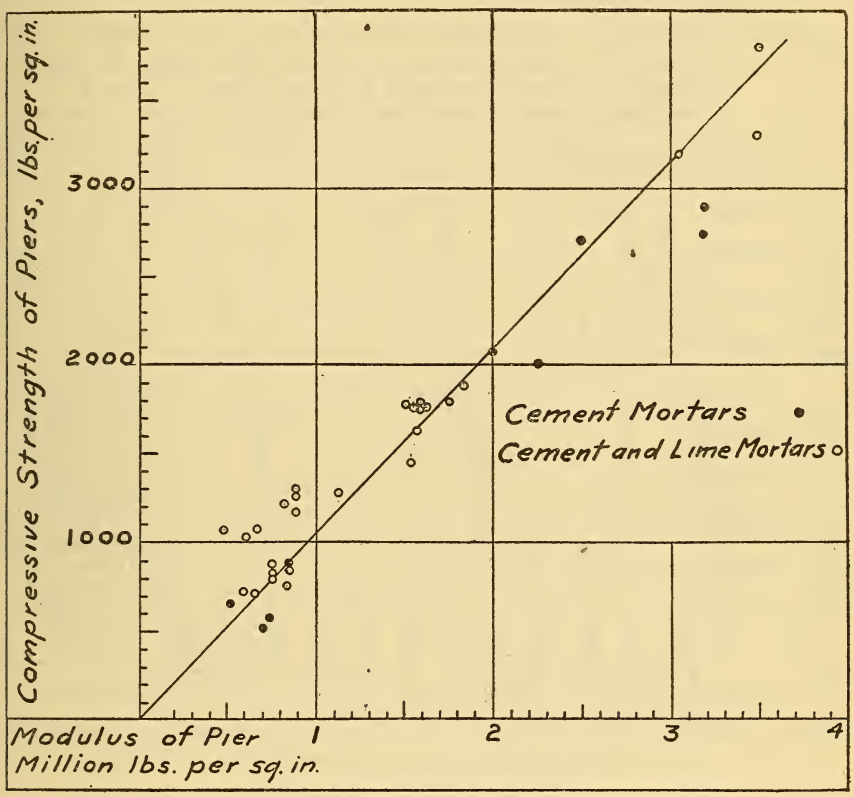


FIG. 22.—*Showing relation of modulus of elasticity to compressive strength of piers*

(D) LATERAL STRAINS.—The type of failure peculiar to brick piers indicates an outward flow of the materials with a consequent tension failure of the individual bricks. Prof. J. B. Johnson [5] implies that for this reason the tensile strength of the brick is a very important quality. Such a condition can be possible only if there is a tendency of the mortar in the horizontal joints to flow faster than the bricks adjacent to the joints. In the present investigation strain measurements were made in the horizontal joints and on the adjacent courses of

[5] Johnson's Materials of Construction, 4th ed., 1907, p. 654.

brick. The results obtained on two representative piers are shown in Figs. 23 and 24. These diagrams show that the strain is sometimes greater in the joints and sometimes greater in courses adjacent to the joints. When the measurements on the four faces of the pier are averaged it is shown that there is no appreciable difference between the strain in the joints and the strain in the adjacent courses.

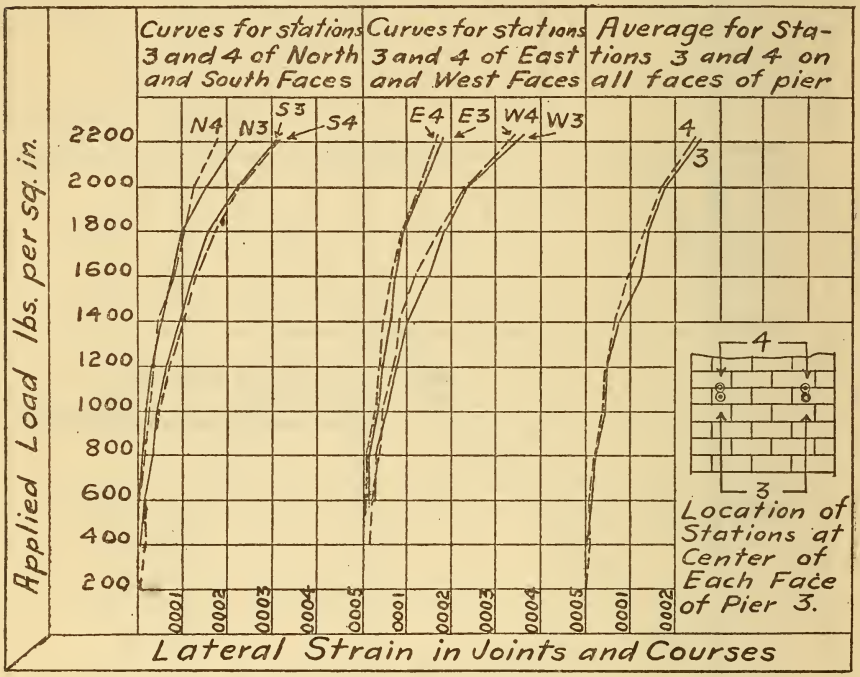


FIG. 23.—*Showing relative strain in horizontal joints and adjacent courses on pier of grade 1 bricks laid in cement mortar*

VI. GENERAL DISCUSSION

1. TYPE OF FAILURE

The type of failure observed in this investigation is in agreement with previous studies of the compressive strength of brick masonry. It may be said, therefore, that failure by vertical cleavage is common to all concentrically loaded brick piers. The first indication of failure appears at about 75 per cent of the ultimate compressive strength of the pier and is indicated by the appearance of hair-size vertical cracks in the individual bricks. These cracks usually start at or quite near the center of the bricks where the bricks break joints with the adjacent courses. The

cracks gradually extend to other courses, and finally, becoming confluent, they extend almost the entire length of the pier. Soon thereafter final failure occurs, accompanied by a spawling off of the outer rings of bricks. In the case of piers of grade 1 bricks laid in lime mortar, sharp reports are heard as the cracks begin to appear, and they increase in frequency with additional load. These reports are peculiar to the failure of bricks by flexure as distinguished from sounds accompanying compression failure. Except in cases of piers laid in mortar of equal or greater strength

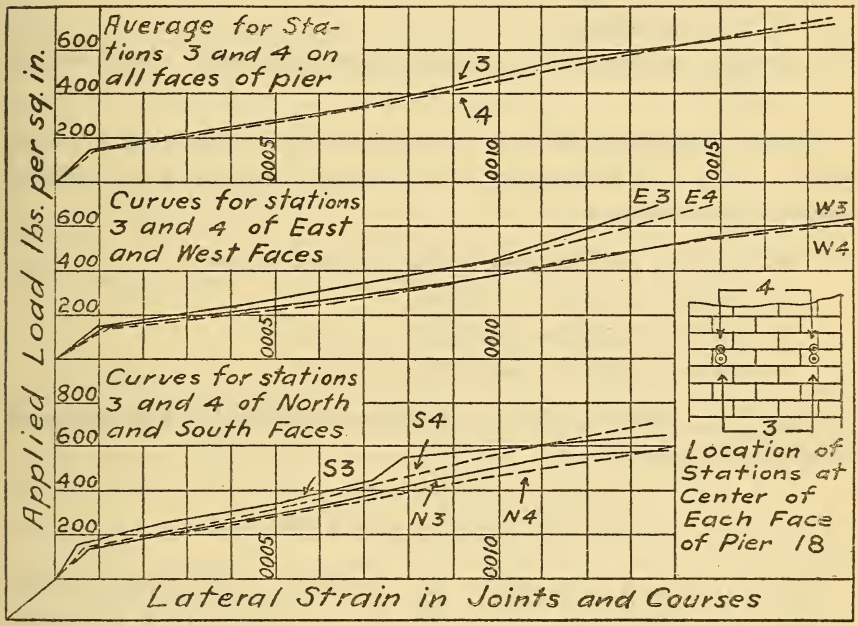


FIG. 24.—*Showing relative strain in horizontal joints and adjacent courses on pier of grade 1 bricks laid in lime mortar*

than the bricks, it is seen after failure that the bricks are broken in two or more pieces and very little crushing of the bricks is apparent. All indications point to a transverse failure of the individual bricks as the cause of incipient failure of the pier. In general, conditions are more favorable to this type of failure of the bricks than to the failure by compression. In most cases the mortar has less stiffness than the brick. Unless all joints are of equal thickness this will cause unequal loading of the individual bricks as the pier is compressed. The same thing will occur when the joints are of equal thickness, but if at the same time the mortar is not distributed over the entire bearing surface of the brick.

Irregularity in the shape of the bricks will result in varying thickness of mortar on their surfaces.

The transverse strength of a single brick varies as the breadth, the depth squared, and inversely as the distance between supports, or

$P = \frac{kbd^2}{l}$. In this equation

P = the breaking load of the brick, in pounds.
b = breadth, in inches.
d = depth in inches.
l = span in inches.
k is an experimental constant depending upon the grade of brick.

As an illustration of how the transverse strength of a single brick varies with the depth, the following values are substituted in the above formula:

k = variable for different grades of brick = 1000,
b = breadth of brick = 4 inches,
d = depth of brick = 2 inches,
l = distance between supports = 7 inches.

Then for a brick in a flatwise position supported at the ends and loaded at the center,

$$P = \frac{1000 \times 4 \times 4}{7} = 2287 \text{ pounds.}$$

When the brick is tested in the edgewise position the breadth is decreased from 4 inches to 2 inches and the depth is increased from 2 inches to 4 inches, then

$$P = \frac{1000 \times 2 \times 16}{7} = 4574 \text{ pounds.}$$

This is twice the strength developed in the flatwise position. It follows, then, that any method of construction which would increase the depth of the bricks or component parts of the pier should increase the strength of the pier. In the Watertown Arsenal tests this was done by laying the bricks on edge, also by breaking joints every sixth course when laid flatwise and every third course when laid on edge. In these tests face brick were laid in 1:1 cement mortar. The following table shows the gain in strength due to the method of construction:

Method of laying bricks	Percentage gain in strength
Bricks flat:	
Joints broken every course	0
Joints broken every sixth course	7.6
Bricks on edge:	
Joints broken every course	43.8
Joints broken every third course	57.3

It is quite probable that the gain in strength due to the method of laying would be greater for softer mortars. That there is a close relation between the transverse strength of the bricks and the ultimate compressive strength of the piers is shown in Fig. 5. The lines connecting the points in this diagram indicate by direction how the strength of the pier follows the strengths of the individual bricks. It is also significant that in the empirical formula given by H. Kreuger a different constant is used for different thickness of brick. He also states that the piers of thinner bricks develop less strength than those of thicker bricks.

2. EFFECT OF QUALITY OF BRICKS

The quality of bricks is obviously a very important factor in the strength of brick masonry. While a high compressive strength of the brick contributes to the ultimate strength of the pier, it is shown also that other qualities of the brick are important in their effect on the compressive strength of masonry. Tests show that the transverse strength of the brick bears a close relation to the strength of the pier. In this respect regularity in shape is essential, since if the bricks are irregular they can not be evenly bedded in the mortar, and this will cause the joints to be thicker than is desirable. Also with bricks of equal compressive strength but of varying depth, the piers built of bricks having the greatest depth will develop higher compressive strengths. The degree of absorption is important in its effect on the strength of the mortar. Very porous brick must be thoroughly "wet down" to prevent absorption of the water in the mortar, which in the case of the richer cement mortars is necessary to the proper hydration of the cement. That the quality of brick with respect to strength is of great importance is seen in Figs. 15 to 20, inclusive, which show that the strength of the piers is proportional to the strengths of the bricks used in their construction.

3. EFFECT OF MORTARS

The importance of proper proportioning of the mortar to be used in brickwork can not be emphasized too strongly. A pure Portland cement mortar, when tested in the form of cubes or cylinders, develops a higher compressive strength than lime or combination cement and lime mortars. Tests show, however, that piers laid in pure Portland cement mortar do not always develop the highest strengths when compared with piers of combination cement and lime mortar. In the present investigation it is seen that there is practically no difference in strength in the piers of pure Portland cement mortar and those of the cement-lime mortar. The cement-lime mortar used was proportioned by weight, 15 per cent of the cement being replaced by hydrated lime. The amount of cement replaced by lime is, therefore, about 35 per cent by volume. The tests made by Macgregor show that in a 1:3 cement and sand mortar 50 per cent of the cement may be replaced by lime without decreasing the strength of 8-inch piers. It is believed, however, that the strengths developed in these tests is higher than would be realized with the same mortar on piers of greater cross sectional dimensions. The greatest advantage in the replacing of a part of the cement with hydrated lime is in the easier working qualities of the cement-lime mortar. Since the cement-lime mortar is more plastic than the pure Portland cement mortar, the bricks may be laid with greater ease and a more nearly uniform bedding of the bricks obtained. That a pure hydrated lime mortar is inefficient in masonry where a high compressive strength is desired is shown conclusively in these tests. The piers of pure lime mortar, although aged four months as compared with one month for the piers of other mortars, showed when broken an almost entire lack of carbonation of the mortar on the interior. It is seen also in Fig. 21 that the cement and cement-lime mortar piers will compress only about one-fourth to one-half as much for the same load as those of the pure lime mortar. A low degree of compressibility is, of course, desirable for masonry in foundations or other parts of a building subjected to compression stresses.

4. EFFECT OF BOND

The opinion prevails that the tying in of the masonry with header courses helps to strengthen the pier against bulging action, thereby increasing the strength in proportion to the number of headers used. Results obtained in the present investigation,

however, show that variations in the number of header courses used do not have a positive effect on the compressive strength of the pier. A comparison of the strength of the piers with respect to the number of header courses is given in the following tabulation:

11 GROUPS OF 3 PIERS EACH

	Number of header courses to stretcher courses		
Compressive strength of pier	1:1	1:3	1:6
Highest	7	1	3
Intermediate	.....	6	5
Lowest	4	4	3

3 GROUPS OF 2 PIERS EACH

Highest	.....	3	.....
Intermediate	.....	.....	.....
Lowest	3	.....	.....

The header course used in these tests, Fig. 1 (*a*), is believed to be the only practicable one which the size of the pier will permit. However, the earlier piers of the Pittsburgh district indicated a decrease in strength of the piers having the greatest number of header courses. It was thought that this effect was probably due to the presence of so many broken or quarter bricks in the corners of the header course. This led to a special study of bond, the results of which are given in Table 2. In these tests pier 48 was built, using header (*c*), Fig. 1. Although this header has fewer broken bricks, it necessitates a special arrangement of the adjacent stretcher courses in order to properly break joints. While the strength of this pier is 6 per cent higher than that of pier 47, in which header (*a*), Fig. 1, was used, the result is not conclusive, since in two piers of exactly the same construction large variations in strength may be expected. In view of the tendency of the individual bricks to fail by flexure, it is believed that the bricks of the header courses are broken through at the joints before the pier has reached that point of failure where these bricks would prevent bulging of the outer rings. For this reason very little increase in strength may be expected by the introduction of header courses. The results obtained on the piers reinforced with wire mesh are in close agreement with those made at Cornell University and indicate that while wire mesh in every horizontal joint increases the strength of the pier, the gain is slight when mesh is used only in every third or fourth course.

VII. SUMMARY

The following conclusions are based on the results of the present investigation and a study of previous tests referred to in Section II:

1. The primary failure of brick piers is caused by a transverse failure of the individual bricks.

2. The ultimate strength of the pier may be increased by any method of construction which will increase the depth of the component parts of the pier. This may be done by (1) laying the bricks on edge instead of flat, (2) breaking joints every few courses instead of every course, or (3) using bricks of more than ordinary thickness.

3. The strength of the pier may be increased by the introduction of wire mesh in all horizontal joints. The increase is slight, however, unless the mesh is used in every joint.

4. Varying the number of header courses used does not appreciably affect the ultimate strength of the pier.

5. The mortar joints should be made as thin as possible. They should be of uniform thickness. For this reason regularity in shape of the bricks is essential.

6. The ultimate strength of brick piers is proportional to the compressive and transverse strength of the bricks used in their construction.

7. The kind of mortar used is important in its effect on the strength of brick masonry. A pure lime mortar is inefficient when a high compressive strength is desired. In a mortar of 1 part Portland cement to 3 parts sand, 25 per cent by volume of the cement may be replaced by hydrated lime without appreciably affecting the strength of brick piers. Higher percentages of lime up to 50 per cent by volume may be used on piers of small cross sectional dimensions.

8. The following empirical formulas for use in computing the strength of brick piers are derived from the tests of the present investigation:

$$(1)\quad P = K\,p$$

$$(2)\quad P = K\,R, \text{ where}$$

P = the ultimate unit compressive strength of the pier,

p = the unit compressive strength of the single bricks,

R = the unit transverse strength or modulus of rupture of the single bricks,

K is a constant depending upon the grade of mortar used, and for which the following values are given.

Mortar	Values to be determined by tests of individual bricks	Value of K
1 (15 per cent lime; 85 per cent cement) to 3 parts sand, by weight.	Unit compressive strength flat=p	0.26
	Unit compressive strength on edge=p	.30
	Modulus of rupture from transverse test=R	1.25
1 part lime to 6 parts sand	Unit compressive strength flat=p	.11
	Unit compressive strength on edge=p	.14
	Modulus of rupture from transverse test=R	.65
1 part cement to 3 parts sand	Unit compressive strength flat=p	.27
	Unit compressive strength on edge=p	.32
	Modulus of rupture from transverse test=R	1.45

Much valuable assistance has been rendered the author throughout the investigation, also in the preparation of this report, and it is desired especially to mention Prof. A. V. Bleininger and J. H. Griffith, of the Bureau of Standards, and Edward Orton, jr., chairman of the technical committee of the National Brick Manufacturers' Association.

WASHINGTON, December 12, 1917.