TEST OF COMPOSITE BEAMS AND SLABS OF HOLLOW TILE AND CONCRETE

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ABSTRACT

Sixty reinforced beams (or slabs), 12 being of concrete and 48 being composite beams representing portions of concrete and hollow tile slabs, were fabricated and tested in the laboratory to determine the value of the tiles in assisting the concrete to resist shear and bending. Among the variable features entering into the construction of the beams were included tiles of different qualities and weights and differences in their position in the beams. The shearing strength of the bond between concrete and hollow tiles was determined also by the testing of 120 specimens representing small portions of hollow tile and concrete slabs.

The results of the beam tests indicated that one row of tiles was equivalent in resisting shear to a concrete rib of the same depth and having a width of from 1.6 to 2.4 inches. At loads considerably less than the maxima the tiles were more effective in increasing the resistance of the beams to bending deformations than at the higher loads. The relatively lower values for the higher loads are believed to be due at least in part to partial failure of the bond between the concrete and tiles.

The strength in shear of the bond between concrete and hollow tile was found to be affected by the factors having an influence on the compressive strength of the concrete. This strength was greatest when concrete containing the least amount of water necessary for its proper placement was used in combination with dry or slightly dampened tiles. The results indicated that the methods followed in the construction and aging of the beams were not favorable to the development of as strong a bond as would have been obtained with different methods.

CONTENTS

	Page
I. Introduction	816
II. The test beams	817
1. Types	817
2. Construction	819
3. Storage	820
III. Materials	821
1. Reinforcement	821
2. Concrete	821
3. Hollow tiles	822
IV. Method of testing beams	824
1. Shear tests of series A and B	824
2. Bend tests of series D	825
V. Results of the shear tests, beams of series A and B	825
1. Cracks and failures	825
2. Method of computing and tabulating results	827
3. Relative value of the shells and the interior webs of the tiles in resisting shear	828
4. Effect of the strength, modulus of elasticity, and absorption of the tiles	829
5. Effect of the position of the joints in alternate rows of the tiles	830
6. Effect of increasing the number of rows of tile between the concrete ribs	831
VI. Summary of data on shear tests of hollow tile and concrete beams	831
1. Comparisons between the results of the 1924 and the 1926 series	831
2. Application of results to design	833

Page
VII. Results of the bend tests, beams of series D 835
1. Types of failure 835
2. Strengths of the beams 837
3. Comparisons between the results of the 1924 and the 1926 series 840
VIII. Tests of the bond between concrete and hollow tile 841
1. The test specimens 841
(a) Type 841
(b) Materials, construction, and aging 842
2. Testing 844
3. Results of the tests 844
(a) Effect of the strength of the concrete on the strength of the bond 844
(b) Effect of the absorption and moisture content of the tiles on the strength of the bond 846
(c) Effect of the curing conditions on the strength of the bond 846
(d) Effect of the proportions of the constituents of the concrete on the strengths of the concrete cylinders and blocks 847
4. Conclusions 848

I. INTRODUCTION

Investigations [1] have shown that hollow-tile fillers add materially to the strength of concrete floors of ribbed construction. Although this is not the chief function of the tiles, it is of obvious economy to take account of their structural values in designing such structures. In attempting to establish a safe allowance for the tiles, the designer is confronted with problems which can not be solved by analysis alone. For information on the strength of the bond between concrete and hollow tile and on the relative values of tiles of different designs and different materials, he must depend upon the results of service and laboratory tests.

In 1924 the Bureau of Standards, cooperating with the Hollow Building Tile Association, completed a series of tests [2] on beams (or slabs) made to represent portions of combination hollow tile and concrete slabs of the 1-way type. Since one of the objects of that investigation was to obtain data on the strength of field-made structures, the beam specimens were built by a contractor who followed the methods commonly used in the construction of buildings for speculation. In that series materials for the concrete in the test beams were not carefully proportioned, and the contractor was permitted to employ without interference the usual rush methods of construction. This procedure was followed in order to lessen the probability of obtaining unduly favorable values which might have resulted from tests of carefully made laboratory specimens.

In a second series of similar tests, completed in 1926, the beam specimens were made under laboratory control in order to minimize variations in the results due to unknown causes. This paper is a report on the second investigation. These later tests deal with the same type of construction and supplement the former series, but some of the specimens were not representative of commercial construction

[1] Slater, Hagener and Anthes, Tests of a Hollow Tile and Concrete Floor Slab Reinforced in Two Directions, B. S. Tech. Paper No. 220. Larson and Petrenko, Loading Test of a Hollow Tile and Reinforced Concrete Floor of Arlington Building, Washington, D. C., B. S. Tech. Paper No. 236. Parsons and Stang, Tests of Hollow Tile and Concrete Slabs Reinforced in One Direction, B. S. Tech. Paper No. 291.

[2] Reported in B. S. Tech. Paper No. 291

either in design or in workmanship. It is thought, however, that, owing to the care used in the construction of the specimens for the later tests, the results give more reliable comparisons between the effectiveness of different types and qualities of tiles than would normally be obtained with specimens constructed under methods used in the first series.

Test data on the relative values in resisting stresses of the outer shells and the interior webs of tiles had not been obtained. Such information was needed as a basis for specifications for floor tiles and as an aid in the selection, from the many varieties manufactured, of a few designs best adapted for use in floor construction. Information was lacking also on the effect of the arrangement of the tiles on the strength of floor slabs and on the factors which govern the strength of the bond between concrete and hollow tiles. Test data relative to these subjects were obtained in the second investigation. Values were obtained for the strength of the bond between concrete and hollow tiles and information on the effects of the following factors on the value of hollow tiles in adding to the strength of tile and joist construction: (1) Quality of the tiles, (2) their weight, (3) number of cells, and (4) the position of the joints in adjacent rows.

The authors are indebted to W. A. Slater, then of the bureau staff, and to F. J. Huse, formerly chief engineer of the Hollow Building Tile Association, for their assistance in planning the investigation. Acknowledgements are due also to the Hollow Building Tile Association (now the Structural Clay Tile Association) for furnishing the materials and labor used in constructing the beam specimens. The bond tests were made by J. C. Oleinik, of the Bureau of Standards.

II. THE TEST BEAMS

1. TYPES

In general, each of the test beams consisted of either 1 or 2 reinforced concrete ribs (beams) similar to those in floors of concrete and hollow tile. Because of differences in the general types of construction represented and in the objects of the tests, the 60 beams included in the investigation are not all comparable with each other. For convenience in conducting the tests and in comparing the results, they are divided into three series—namely, series A having 27 beams, series B with 18, and series D with 15.

The specimens of all series, however, were similar in some features. The materials used in their construction were alike except the tiles; the concrete ribs in all combination beams were 4 inches in width; all were 8 inches in depth and contained two ⅞-inch diameter round steel bars in each rib for tensile reinforcement. In each series there were comparison beams of concrete which were identical in size and design to the concrete portion of either one or two of the ribs of the combination beams of the same series. The dimensions and details of the beams are shown in Figures 1 and 2. Photographs taken after test of one beam of each type are shown in Figures 5, 6, and 7. Table 1 gives the type of hollow tiles used in each beam. Photographs of samples of the tiles are shown in Figure 3. In designating the beams of one type two letters are used, the first being the series and the second the type of that series. Since three beams of each type were made,

a numeral added to the two letters is used to designate a single beam; that is, AC–1, AC–2, and AC–3 designate the three identical beams of the one type (C) of series A.

TABLE 1.—*Schedule of test beams and types of hollow tile used*

Beams	Hollow tiles			
	Lot No.	Type	Kind of clay	Joints
AA	-----	Concrete beams	No tiles used	
AB	-----	do	do	
AC	1	6-cell, 8 by 12 by 12 inch	Ohio fire clay	Staggered.
AD	4	do	New Jersey fire clay	Do.
AE	8	do	Indiana surface clay	Do.
AF	6	2-cell, 8 by 5 by 12 inch	New Jersey fire clay	
AG	3	6-cell, 8 by 12 by 12 inch	do	
AH	4	do	do	
AI	5	4-cell, 8 by 12 by 12 inch	do	
BA	-----	Concrete beams	No tiles used	
BB	2	3-cell, 6 by 12 by 12 inch	Ohio fire clay	Do.
BC	7	do	New Jersey fire clay	Do.
BD	9	do	Indiana surface clay	Do.
BE	7	do	New Jersey fire clay	Opposite.
BF	5	4-cell, 8 by 12 by 12 inch	do	Staggered.
DA	-----	Concrete beams	No tile used	
DB	3	6-cell, 8 by 12 by 12 inch	New Jersey fire clay	Do.
DC	4	do	do	Do.
DD	5	4-cell, 8 by 12 by 12 inch and 6-cell, 8 by 12 by 12 inch	do	Do.
DE	4		do	Opposite.

The beams of series A and B were tested to produce high shearing stresses. They were heavily reinforced for bending stresses to force failures in shear, the area of the tensile reinforcement being 4.45 per cent of the nominal sectional area of the concrete lying above the mid plane of the bars. In these beams each rib contained, in addition to the tensile renforcement, two ¾-inch diameter round steel bars as compressive reinforcement. Each of the beams of series B contained four ⅜-inch diameter round steel bars as transverse reinforcement in the concrete topping. These bars were similar in size, spacing, and position to the reinforcement for stresses due to shrinkage and changes in temperature which are frequently used in floors of this type.

The beams of series A afford comparisons to determine the effects of the strength of the tiles, their weight, and the number of vertical interior webs on the resistance of the tiles to diagonal tension.

Series B represents specimens of a construction similar to ribbed floors with a concrete topping over tile fillers. The beams were constructed with the topping on the upper surface, but were tested with the topping in tension to simulate conditions at the interior supports of continuous construction. In this series are represented three different arrangements of the tiles and also tiles of three different strengths arranged in the same manner.

The beams of series D contained no compressive reinforcement and were tested to produce high bending stresses. They were heavily reinforced for tension in order to permit the development of high compressive stresses in the concrete and tiles. The tiles for the beams were manufactured at one plant from clay obtained from one source, but the three types used differed in weight and design.

2. CONSTRUCTION

The test beams were built in the laboratories of the Bureau of Standards by labor supplied by the Hollow Building Tile Association working under supervision of members of the bureau staff. The placing of the concrete for series A and B was on one day of each week for three consecutive weeks. Fifteen beams, one of each type, were made in

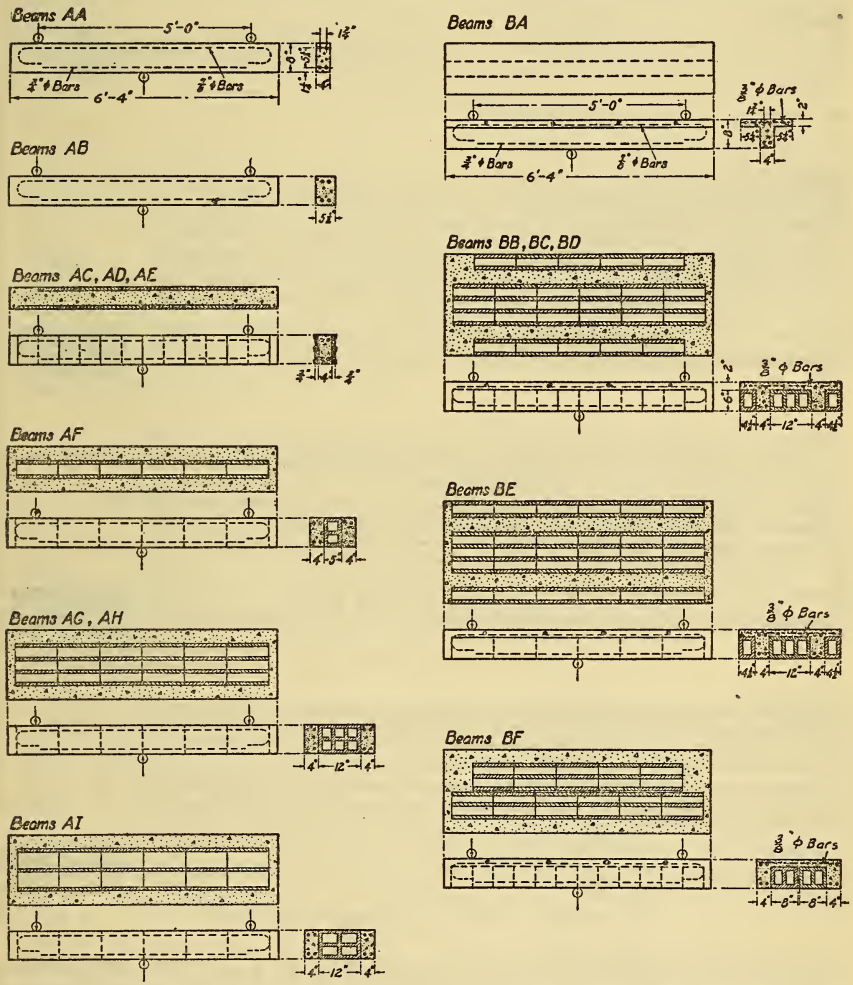

FIGURE 1.—*Details of the beams of series A and B*

one day. Similarly, the beams of series D were made during a period of three weeks, one of each type being cast on each of the three construction days. For example, those designated A–1 and B–1 were made on the same day, and the beams designated A–2 and B–2 were all made on another day.

The construction procedure was the same for the specimens of all series. Wood forms were prepared for the beams built in one day, and the tiles and reinforcement were fixed in position before any con-

crete was placed. In order to prevent concrete from flowing into the cells, the open ends of the tiles were blocked with fragments of broken tiles. The tiles and forms were then thoroughly wetted about one-half hour before and again immediately preceding the pouring of the concrete.

The materials for the concrete were proportioned by weight. After mixing in a drum mixer, the concrete was dumped into a wooden box,

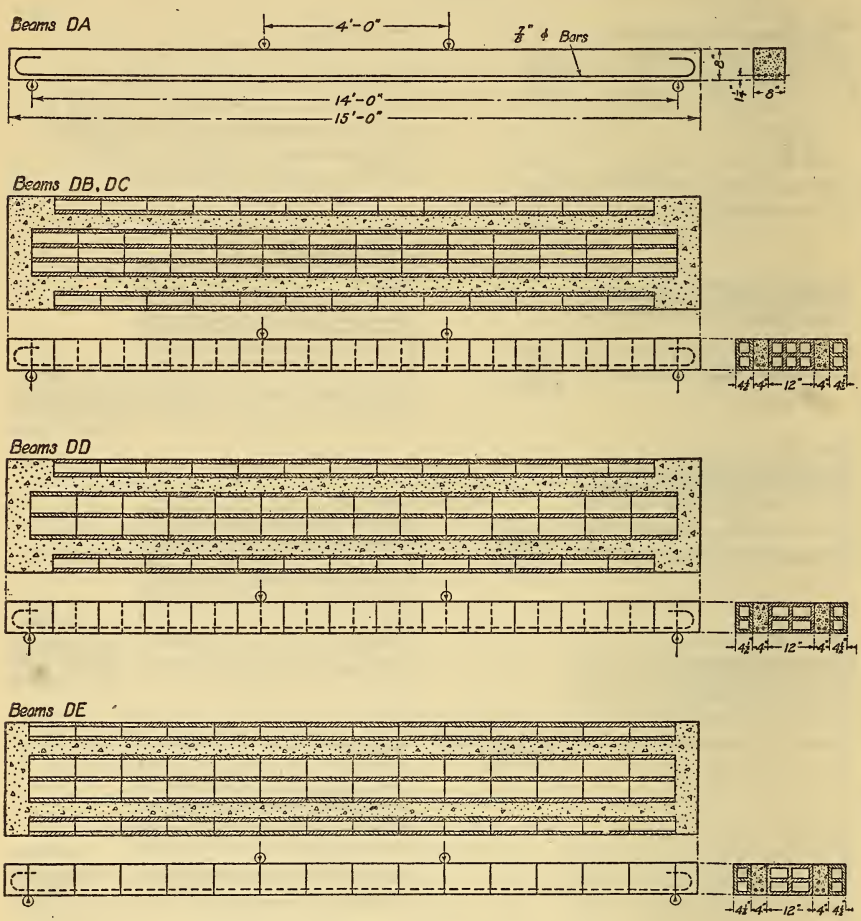

FIGURE 2.—*Details of the beams of series D*

shoveled into wheelbarrows for transporting to the forms, and placed with shovels. Large trowels were used to compact the fresh concrete in the forms, and care was taken to work the concrete around the tiles and reinforcement.

3. STORAGE

Within 2 hours after the concrete was placed, the beams were covered with damp burlap; when 2 days old, they were removed from the forms and placed in piles under burlap kept damp. The beams remained in damp storage until 28 days old and were then permitted to dry in the laboratory for approximately 2 weeks before testing.

III. MATERIALS

1. REINFORCEMENT

The steel reinforcement consisted of round deformed bars. The ⅞-inch bars used as tensile reinforcement conformed to the requirements for "hard" grade and the ¾-inch bars used as compressive reinforcement met the requirements for "intermediate" grade of specification A15–14 of the American Society for Testing Materials.[3] No tests were made on samples of the ⅜-inch diameter bars used as transverse reinforcement in the beams of series B.

2. CONCRETE

The materials for the concrete were purchased locally, and a sufficient quantity for all of the beams was delivered before beginning construction. The cement met the requirements of specification C9–21 for Portland cement of the American Society for Testing Materials. The aggregate consisted of Potomac River sand and gravel similar to the material used locally in building construction except that the gravel was passed through a screen with ¾-inch diameter openings. Gravel of larger size was not used because of the narrow spaces between the bars. The results of sieve analyses of the sand and gravel are given in Table 2.

TABLE 2.—*Sieve analysis and weight of concrete aggregates*

Aggregate	Sieve analysis. Amount retained on each sieve (per cent by weight)								Fineness[1] modulus of aggregates	Weight when dry and rodded
	100	50	30	16	8	4	⅜	¾		
										Lbs./ft.[3]
Sand	96	85	56	41	24	3	0	------	3.05	110
Gravel	100	100	99	99	97	74	13	0	5.82	102
Combined[2]	98	93	80	73	64	41	7	0	4.56	119

[1] Sum of per cents in sieve analysis divided by 100.
[2] Sand and gravel combined in the proportions used in the concrete.

Tests were made to determine the proportion of sand to gravel which yielded the mixture having the greatest density when in a dry and rodded condition. The mixture used contains approximately 10 per cent more gravel than the one giving the maximum density. Trial batches of hand-mixed concrete were made with the aggregates combined in the selected proportions, to determine the amount of cement and water required to make concrete of the desired consistency. For these batches varying amounts of cement and water were added to the sand and gravel; but in each the volume of water equaled the volume of cement. The mix selected for the concrete of the beams consisted of cement and combined sand and gravel in the volume proportions of 1 :3.7. Expressed in terms of the volumes of dry rodded aggregates measured separately, the proportions were 1 :1.84 :2.33, respectively, for the cement, sand, and gravel.

The materials for the concrete of the beams were proportioned by weight. Samples of the sand and gravel were tested for moisture content; and allowances were made, in weighing the aggregate and water, for the moisture in the aggregates. Each batch consisted of 60 pounds of cement, 129 pounds of dry sand, 152 pounds of dry

[3] 1927 Book of A. S. T. M. Standards, Pt. I, p. 132.

gravel, and 44 pounds of water. Of the 44 pounds of water, 4 pounds were allowed for the absorption of the aggregates and the remaining 40 pounds were considered effective in calculating the water-cement ratio. The batches were mixed in a drum mixer for two minutes and then dumped into a box. Samples were then taken for slump tests and for making control cylinders.

Two 6 by 12 inch cylinders were made in steel molds from the concrete of one of the batches for each beam. They were capped with neat cement and removed from the molds within 48 hours, one being stored in the damp room of the concrete laboratory and the other with its corresponding beam. The cylinders stored in the damp room were tested when 28 days old; the others remained with the beams, being kept under damp burlap for 28 days and then in dry storage for 14 days before testing.

The results of the tests of the concrete are given in Table 3. The values, both for slump and for compressive strength, were higher than anticipated from the results of the trial batches of hand-mixed concrete. The average slump from the trial batches was about 7 inches, whereas for the machine-mixed concrete of the same proportions the average slump exceeded 9 inches. The average strength at the age of 7 days of the concrete from hand-mixed batches was 1,050 lbs./in.^{2}; and the strength of 12 cylinders, at the same age, from the machine-mixed concrete for the beams was 1,340 lbs./in.^{2}.[4]

TABLE 3.—*Results of tests of the concrete*

Sample from beams	Slump	Compressive strength at—	
		28 days	42 days
	Inches	*Lbs./in.*^{2}	*Lbs./in.*^{2}
AA	9.1	2,510	3,210
AB	9.4	2,890	3,200
AC	9.5	2,740	3,100
AD	9.0	2,610	3,070
AE	9.5	2,280	2,760
AF	9.1	2,770	3,260
AG	9.3	2,870	3,130
AH	9.4	2,730	3,060
AI	9.0	2,930	3,100
Average	9.3	2,700	3,100
BA	9.4	2,660	2,940
BB	9.6	2,580	2,800
BC	9.0	2,630	2,900
BD	9.0	3,020	3,360
BE	9.4	2,690	3,150
BF	9.5	2,940	3,000
Average	9.3	2,750	3,020
DA	9.6	2,660	3,140
DB	9.4	2,820	3,250
DC	9.4	2,640	2,960
DD	9.8	2,550	2,990
DE	9.8	2,700	3,100
Average	9.6	2,670	3,090

NOTES.—Averages for series A and B (weighted), slump 9.3 inches, strength at 28 days 2,720 lbs./in.^{2}, and strength at 42 days 3,070 lbs./in.^{2}.

Averages for series A, B, and D (weighted), slump 9.4 inches, strength at 28 days 2,710 lbs./in.^{2}, and strength at 42 days 3,070 lbs./in.^{2}.

3. HOLLOW TILES

Nine different lots of hollow tiles were used in the construction of the beams. The types are illustrated in Figure 3 and are listed in Table 4. Two lots were made by a plant in Ohio, five by a plant in New Jersey, and the other two by a plant in Indiana.

[4] Results not included in Table 3.

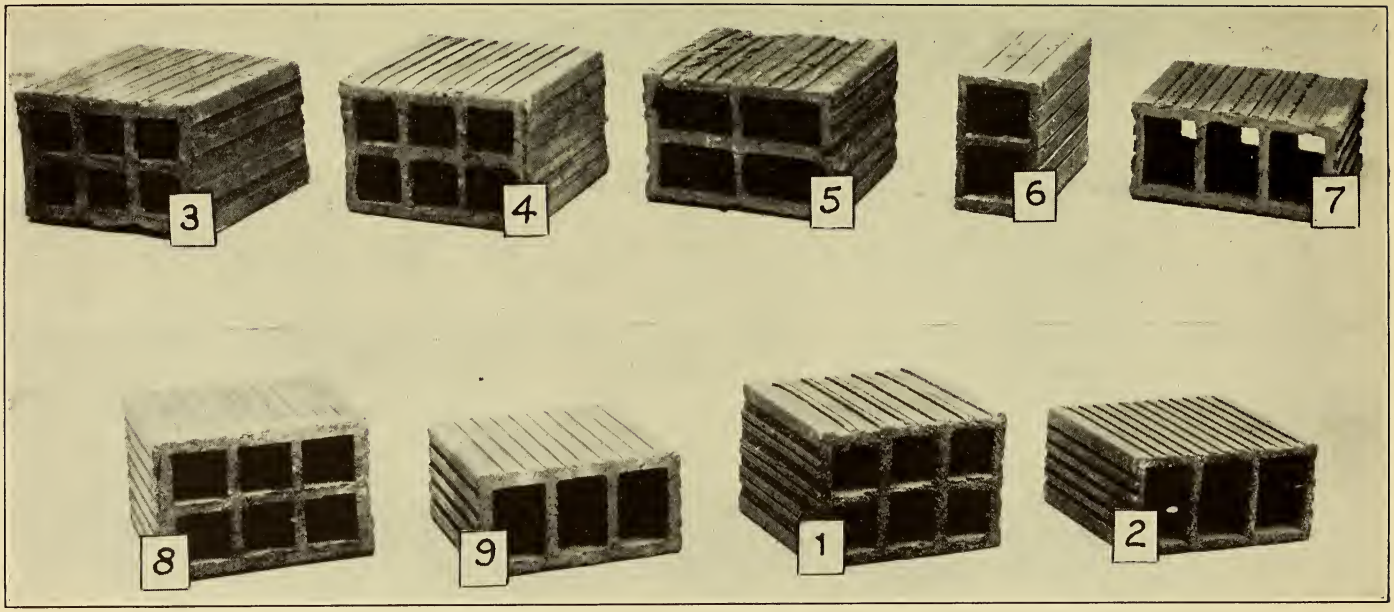

FIGURE 3.—*The hollow tiles*

The numbers refer to the type or lot number.

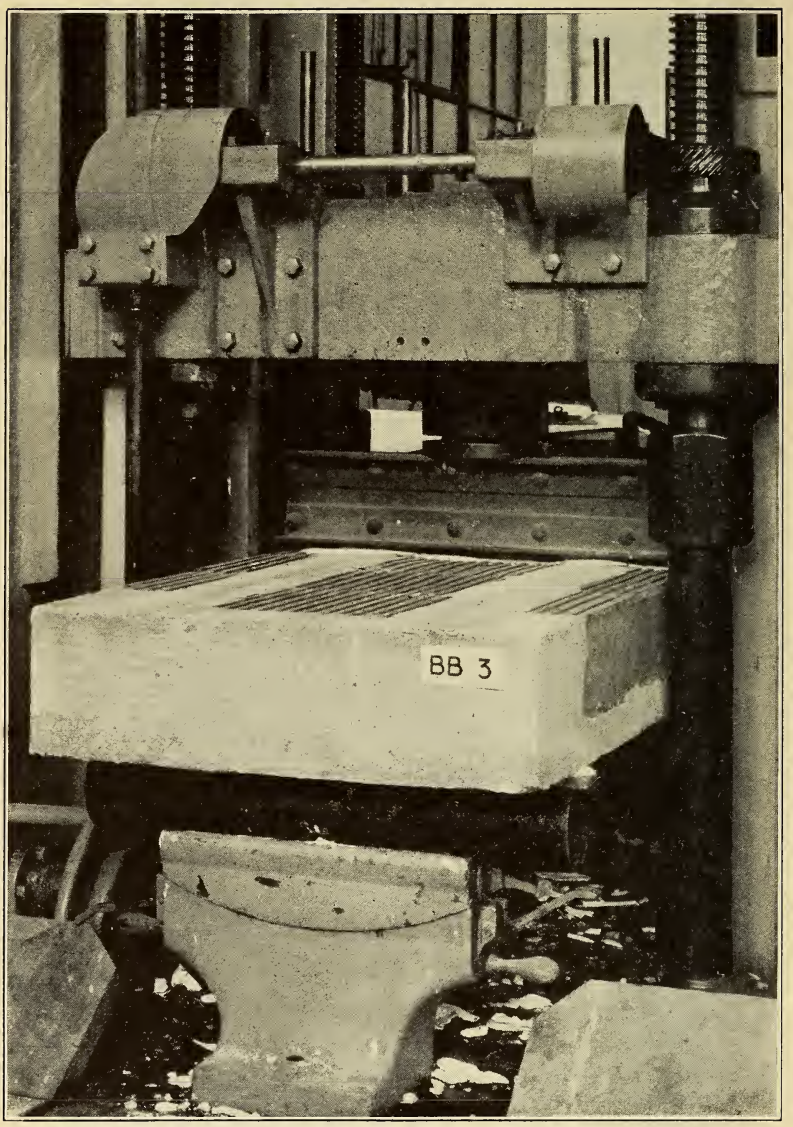

FIGURE 4.—*Beam BB–3 in testing machine for the shear test*

TABLE 4.—*Results of tests of the hollow tiles*

[Each value is the average for 10 tests]

Lot No.	Hollow tiles		Thickness of shells vertical in beams	Weight			Compressive strength		Modulus of elasticity (net area)	Absorption	
	Type	Material		Total	Gross volume	Net volume	Gross area	Net area		24-hour immersion	1-hour boiling
			Inch	*Pounds*	*Lbs./ft.*[3]	*Lbs./ft.*[3]	*Lbs./in.*[2]	*Lbs./in.*[2]	*Lbs./in.*[2]	*Per cent*	*Per cent*
1	6-cell, 8 by 12 by 12 inches	Ohio fire clay	0.74	33.1	51.0	125	2,490	6,080	3,460,000	6.1	10.1
1W	do	do	.74	33.0	50.9	125	[1] 2,250	[1] 5,520	[1] 3,440,000	6.4	10.5
2	3-cell, 6 by 12 by 12 inches	do	.60	20.2	43.2	130	2,410	7,230	4,550,000	4.5	7.9
3	6-cell, 8 by 12 by 12 inches	New Jersey fire clay	.94	38.5	57.2	118	1,870	3,860	2,580,000	9.6	14.4
3W	do	do	.94	38.4	56.7	117	[1] 1,750	[1] 3,620	[1] 2,520,000	10.0	14.8
4	do	do	.78	33.9	51.1	118	1,630	3,770	2,890,000	10.3	14.1
5	4-cell, 8 by 12 by 12 inches	do	[2] .83	30.1	44.7	118	1,140	3,020	2,490,000	11.1	14.0
6	2-cell, 8 by 5 by 12 inches	do	.71	15.7	56.0	120	1,870	4,000	3,170,000	9.8	13.6
7	3-cell, 6 by 12 by 12 inches	do	.69	21.0	44.2	124	1,850	5,210	4,050,000	7.0	10.3
8	6-cell, 8 by 12 by 12 inches	Indiana surface clay	.92	31.1	46.4	105	1,250	2,870	1,740,000	22.6	24.1
8W	do	do	.92	30.8	46.0	106	[1] 1,150	[1] 2,680	[1] 1,630,000	22.4	23.9
9	3-cell, 8 by 12 by 12 inches	do	.80	21.4	43.7	108	1,730	4,260	1,930,000	20.9	22.3

[1] Tested when wet, after 24 hours immersion in water at 70° F.

[2] In beams BF, thickness was 0.76 inch.

Ten tiles of each lot were selected by appearance to cover the range in burning for the customary physical tests of the individual tiles. In so far as applicable, the methods described in specification C34–27 [5] of the American Society for Testing Materials were followed in conducting these tests. For the compressive tests, the tiles were loaded parallel to the direction of the cells. The results of the tests are given in Table 4. In addition to the 10 tiles of each lot tested in the dry condition, 10 samples of each of lots 1, 3, and 8 were tested for compressive strength and modulus of elasticity immediately after being immersed in water at room temperature for 24 hours. These auxiliary tests of saturated tiles were made to determine the effect of moisture on their strength and stiffness, since the tiles in the beams probably were not completely dry at the time of test. The results indicate that the presence of moisture in the tiles did not greatly lessen their strength; in no case was the reduction in strength greater than 10 per cent. The slight reduction in strength indicated by the values in Table 4 probably is somewhat greater than the true values, since the strength of both gypsum and cement, of which the capping materials were composed, is known to be reduced by the presence of moisture.

IV. METHOD OF TESTING BEAMS

1. SHEAR TESTS OF SERIES A AND B

The position of the beams in the forms was the same as shown in Figures 1 and 2; those of series D were tested in the same position, while, for convenience in applying the loads, those of series A and B were inverted before testing. It was desired that the beams of series A and B represent portions of slabs in regions of negative bending moment. These beams were accordingly built and loaded to cause the surfaces which were uppermost when constructed to be in tension during the tests.

All of the beams were tested in a vertical screw universal testing machine having a capacity of 600,000 pounds. As indicated in Figures 1 and 2, the beams of series A and B were supported over a span of 5 feet spaced symmetrically about the center of the beams and the loads applied at mid span, while those of series D were supported over a span of 14 feet and loaded along two lines, each being 2 feet from mid span. The type of supports and methods of transmitting the loads to the beams are illustrated by the photographs of beams BB–3 and DD–2 shown in Figures 4 and 5.

For the tests of series A and B, the machine was run continuously so as to cause a lowering of the moving (upper) head at the rate of 0.04 inch per minute from the time a test was started until its completion. As the loading progressed, records were kept describing the development of cracks and of the loads at the time each new crack appeared. Each test was stopped when the magnitude of the load and the appearance of the beam indicated that the maximum load had been passed.

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[5] 1927 Book of Am. Soc. Test. Mats. Standards Pt. II, p. 213.

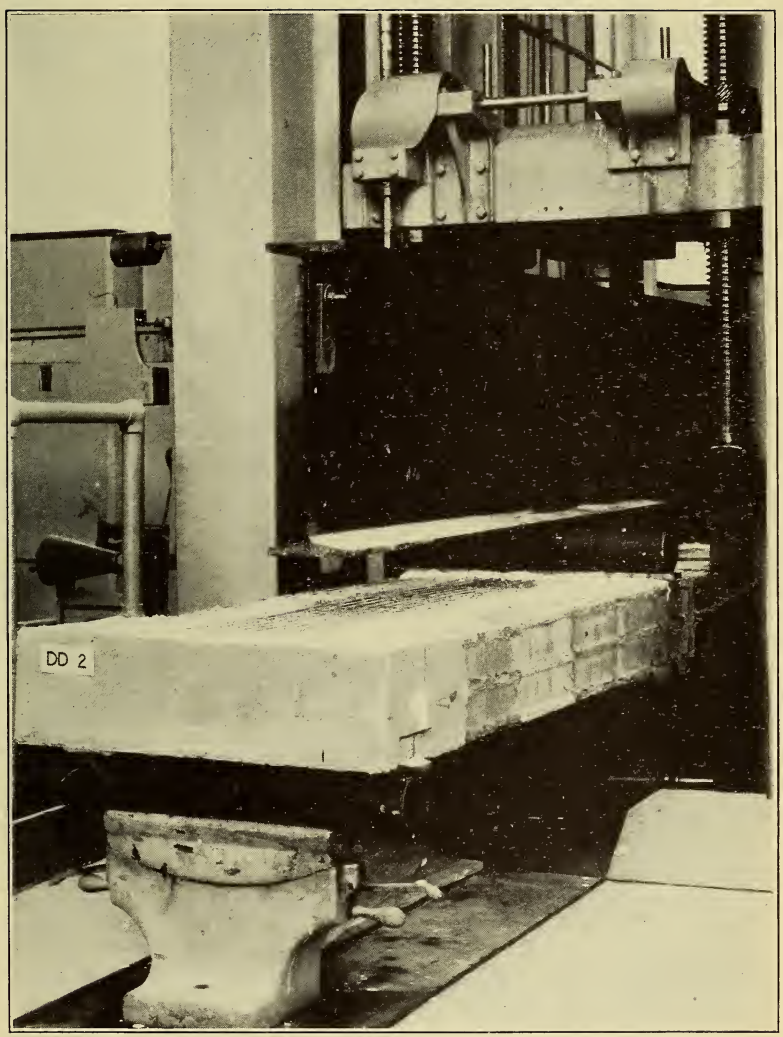

FIGURE 5.—*Beam DD–2 in testing machine for the bend test*

FIGURE 8.—*Typical beams of series B after testing*

2. BEND TESTS OF SERIES D

With series D, measurements were made of the deflections of the beams and of the strains in the concrete, steel, and tiles. The deflections were measured at mid span of the beams on mirror scales, graduated to 0.1 inch, by means of a fine wire fastened to the beams directly over the supports and kept taut with rubber bands. Tensile longitudinal deformations in the steel and compressive longitudinal deformations in the concrete and tiles were measured by strain gages over 8-inch gage lengths located approximately at mid span. There were two gage lines in the reinforcement of each beam, one in each of the two outer bars. One gage line was located on the upper surface of each concrete rib, while those in the tiles were on the upper surfaces, one being above each of the vertical webs and shells.

In making a test a set of observations was made before applying load, and then other sets were made after each 2,000-pound increase in the load until the measurements indicated that either the steel or the concrete had begun to yield appreciably with a constant load on the beam. In most cases the readings were continued to within 10 per cent of the maximum loads. The instruments were then removed, and the machine run continuously until the maximum load had been passed.

V. RESULTS OF THE SHEAR TESTS, BEAMS OF SERIES A AND B

1. CRACKS AND FAILURES

The failures of all of the beams of series A and B were accompanied by the appearance of diagonal cracks extending from the lower portion of the beam near a support toward the upper surface at mid span. The diagonal cracks in the tiles were approximately in the same plane and of about the same length as the cracks in the concrete of contiguous ribs. Photographs of the beams taken after test are shown in Figures 6, 7, and 8.

In the beams without a topping over the tiles (series A) no diagonal cracks were evident until the maximum load was reached. The failure of each of these beams was sudden and occurred simultaneously with the formation of a diagonal crack in one end of a beam.

In some of the beams with a topping over the tiles (series B) diagonal cracks became visible before the maximum load had been reached. The first diagonal cracks in these beams were noted at loads ranging from 66 to 100 per cent of the maximum. On the average, the first crack appeared at a load of 94 per cent of the maximum.

The results of the tests are given in Table 5. All computed quantities were calculated by the methods used in common practice, the beam formulas employed being those given in the 1924 report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete.[6] For these calculations a value of 12 for the ratio (n) of the modulus of elasticity of the steel to that of the concrete was assumed.

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[6] Proc. Am. Soc. for Test. Mats., XXIV Pt. I, p. 313; 1924. Also published in the proceedings of other technical organizations and reprinted in books on concrete construction.

TABLE 5.—*Series A and B, dimensions of beams and results of tests*

Depth to tensile reinforcement ..... d=6.8 inches.
Depth to compressive reinforcement ..... d'=1.3 inches.
Area of tensile reinforcement in each rib ..... A_s=1.20 square inches.
Area of compressive reinforcement in each rib ..... A_s'=0.88 square inch.

A, CONCRETE BEAMS (SERIES A AND B)

Beam No.	Width of concrete rib b	j	Maximum load W	Maximum shearing stress $v=\frac{V}{bjd}$
	Inches		*Pounds*	*Lbs/in.*^{2}
AA-1	4.20	0.820	9,200	196
AA-2	4.25	.820	8,750	185
AA-3	4.68	.822	8,600	164
Average				182
AB-1	5.60	.827	11,600	184
AB-2	5.85	.828	11,500	175
AB-3	5.85	.828	12,850	195
Average				185
BA-1	4.00	.819	9,000	202
BA-2	3.90	.818	9,250	213
BA-3	3.98	.819	9,750	220
Average				212

B, COMBINATION BEAMS WITHOUT A TOPPING (SERIES A) (j ASSUMED AS 0.83)

Beam No.	Lot No. of tile in beam	Total width of beam	Total width of concrete ribs	Maximum load W	Width of concrete web equivalent in shearing strength	Width of concrete web equivalent to 1 inch of tile shell
		Inches	*Inches*	*Pounds*	*Inches*	*Inches*
AC-1	1	5.47	3.99	12,000	5.79	1.22
AC-2	1	5.62	4.14	13,900	6.71	1.74
AC-3	1	5.65	4.17	12,750	6.15	1.34
Average						1.43
AD-1	4	5.78	4.22	11,800	5.70	.95
AD-2	4	6.02	4.46	13,300	6.42	1.26
AD-3	4	5.70	4.14	13,000	6.28	1.37
Average						1.19
AE-1	8	5.75	3.93	12,000	5.79	1.02
AE-2	8	5.90	4.08	13,250	6.40	1.27
AE-3	8	5.90	4.08	10,650	5.14	.58
Average						.96
AF-1	6	13.00	7.89	19,000	9.17	.91
AF-2	6	13.10	7.99	21,750	10.50	1.77
AF-3	6	13.15	8.04	20,600	9.96	1.35
Average						1.34
AG-1	3	20.00	7.84	19,000	9.17	.71
AG-2	3	20.05	7.89	21,800	10.52	1.40
AG-3	3	20.08	7.92	20,650	9.97	1.09
Average						1.07
AH-1	4	20.10	7.99	18,700	9.03	.67
AH-2	4	20.15	8.04	20,200	9.75	1.10
AH-3	4	20.18	8.07	19,700	9.51	.92
Average						.90
AI-1	5	20.22	8.09	20,800	10.04	1.18
AI-2	5	20.20	8.07	22,600	10.91	1.71
AI-3	5	20.30	8.17	22,150	10.69	1.52
Average						1.47

TABLE 5.—*Series A and B, dimensions of beams and results of tests*—Continued

C, COMBINATION BEAMS WITH A TOPPING (SERIES B) (*j* ASSUMED AS 0.83)

Beam No.	Lot No. of tile in beam	Total width of beam	Total width of concrete ribs	Maximum load *W*	Width of concrete web equivalent in shearing strength	Width of concrete web equivalent to 1 inch of tile shell
		Inches	*Inches*	*Pounds*	*Inches*	*Inches*
BB-1	2	28.45	8.09	29,650	12.40	1.80
BB-2	2	28.70	8.34	34,450	14.40	2.52
BB-3	2	28.90	8.54	30,600	12.79	1.77
Average						2.03
BC-1	7	29.20	8.59	29,200	12.21	1.31
BC-2	7	29.05	8.44	30,400	12.71	1.55
BC-3	7	28.88	8.27	30,700	12.83	1.65
Average						1.50
BD-1	9	28.85	8.13	27,750	11.59	1.07
BD-2	9	28.90	8.18	28,600	11.95	1.17
BD-3	9	28.40	7.68	24,900	10.41	.85
Average						1.03
BE-1	7	29.00	8.39	29,600	12.37	1.44
BE-2	7	29.28	8.67	29,300	12.24	1.29
BE-3	7	29.15	8.54	30,050	12.56	1.46
Average						1.40
BF-1	5	24.00	7.75	23,550	9.84	1.38
BF-2	5	24.15	8.00	23,450	9.80	1.18
BF-3	5	24.25	8.10	22,800	9.53	.95
Average						1.17

Each rib of the beams of series A and B contained two ⅞-inch round bars as tensile reinforcement and two ¾-inch round bars as compressive reinforcement. Measurements indicated that the depth of the beams from the extreme fiber in compression to the center of the compressive reinforcement was 1.3 inches within ±0.1 inch and to the center of the tensile reinforcement was, within the same limits, 6.8 inches.

2. METHOD OF COMPUTING AND TABULATING RESULTS

The strengths of the concrete beams AA and AB are taken as a measure of the strength of the concrete ribs of the combination beams of series A. Similarly, the strength of the concrete beams BA serve as a measure of the strength of the concrete portions of the other beams of series B. Owing to differences in the dimensions of the beams and the tiles, the maximum loads supported by the beams are not direct measures of the value of 1 unit width (or thickness) of tile in increasing the strength of the combination beams. A convenient method of making an allowance, in design, for the additional strength given by the tiles is to consider that their effect is equivalent to an increase in the widths of the concrete ribs. In Tables 5, B and 5, C are given the widths of concrete webs equivalent to 1 inch of tile shells for each of the combination beams. The following examples illustrate the method of calculating these widths from the test data.

In series A there were two sets (AA and AB) of concrete beams, the beams of each set being, except for width, of identical design. Beams AA had approximately the same width as the concrete ribs of combination beams. Beams AB having a greater width, were included to determine whether there would be an appreciable difference in maximum shearing stress due solely to an increase in the width of the beam. Since the maximum shearing stresses (Table 5, A) were about the same for the two sets, the average strength of the six beams (AA and AB) was taken as a measure of the resistance of the concrete ribs of the combination beams of series A. Using this average value (184 lbs./in.^{2}) for the resistance of the concrete to shearing stress, the widths of rectangular concrete beams of the same depth required to resist the loads supported by each of the combination beams of series A were computed by the following formula:

$$b=\frac{W}{2vjd}$$

where

W = the maximum load, pounds, supported by a combination beam.
v = 184 lbs./in.^{2}, the average maximum shearing stress for the concrete beams AA and AB.
j = taken as 0.83 for all combination beams.[7]
d = 6.8 inches.

These widths may be considered as the widths of concrete beams equivalent in resisting shear to a corresponding tile and concrete beam. Deducting from the width b the total width of the concrete in a beam gives the width of concrete equivalent to the effect of the tile in increasing the shearing resistance of the beam. These values expressed in terms of the total thickness of the vertical tile shells, having a bond contact with the concrete, are given in Table 5, B.

For the beams of series B, the values of the tiles in increasing the shearing resistance of the beams were calculated in the same manner, the only difference being that the shearing stress (v) was taken as 212 lbs./in.^{2}, the average for beams BA.

3. RELATIVE VALUE OF THE SHELLS AND THE INTERIOR WEBS OF THE TILES IN RESISTING SHEAR

The results from the tests of beams AF, AG, AH, and AI may be compared to determine the effect of the number of cells in the tiles on their value in resisting shear. In beams AF there were no vertical interior webs, in beams AI there was one, and in beams AG and AH there were two. The tiles for these beams were manufactured by one plant and from one source of material, and there was not a large difference in the strength of the material. The values given in Table 5, B indicate that there was no relation between the effectiveness of the tiles and the number of cells. It is seen also that, on the average, the value of the tiles in these beams was about the same as for beams

[7] Because of the effect of the tiles, the values of j (ratio of lever arm of resisting couple to the depth d) for the combination beams differed somewhat from those based upon the concrete section only of the beams. Since the amount of this difference is not known, and since relatively large changes in the effective widths are required to produce important changes in the values of j, a constant value (j=0.83) was used in the calculations pertaining to the combination beams of series A and B.

AD having only shells of tiles manufactured by the same plant. It may be concluded, therefore, that the interior webs of the tiles were of little if any value in increasing the resistance of the beams to shear and that the resistance of the tiles was due almost entirely to the vertical shells bonded to the concrete ribs.

4. EFFECT OF THE STRENGTH, MODULUS OF ELASTICITY, AND ABSORPTION OF THE TILES

In series A the beams AC, AD, and AE were of identical design except for the quality of the tiles; the results for these beams may be compared, therefore, to determine the effect of the physical properties of the tiles on their values in increasing the strength of the beams. A comparison between the compressive strengths of the tiles and the widths of concrete equivalent in shear to each inch width of tile shells in these beams is shown by the filled circles in Figure 9. The

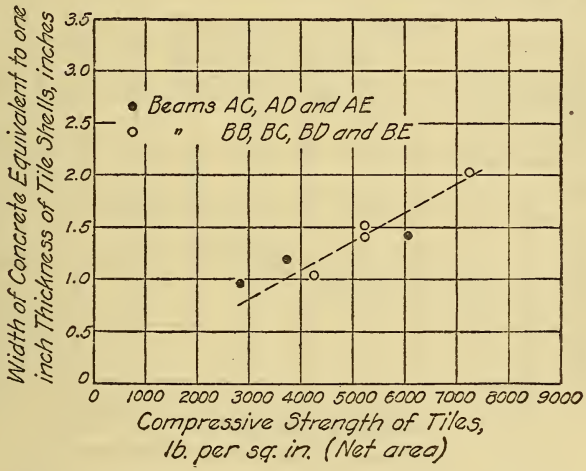

FIGURE 9.—*Relation between the compressive strength of the tiles and their value (per unit thickness of shells) in resisting shear in the beams*

results for the beams BB, BC, and BD, which were identical except for the tiles, are shown by the open circles in the same figure.

The results shown in Figure 9 indicate that, in general, the assistance of the tiles increased with an increase in the compressive strength of the tiles. With tiles having a compressive strength greater than the average strength of the concrete cylinders (3,070 lbs./in.^{2}), the effect of the tiles in resisting shear was equivalent to an increase in the widths of the concrete webs greater than the thickness of the tile shells in contact with the concrete.

The strength of the beams of series B was on the average greater per unit of width of the concrete ribs than for the beams of series A. With the value of the tiles expressed in terms of the strength of the concrete beams, it is seen from Figure 9, however, that there was not a great difference between the assistance of the tiles in the two series; that is, although the maximum shearing stress for beams BA was greater than for beams AA and AB, the effect of the tiles in the beams

with a topping was also somewhat greater than without the topping; and the results indicate that the value of the tiles in increasing the resistance of the beams to shear was about the same in the two types of construction when expressed in terms of equivalent widths of concrete.

Figure 10 shows a comparison between the modulus of elasticity of the tiles and their value in resisting shear. Though the points are somewhat scattered, their positions indicate a general increase in shearing resistance with an increase in the modulus of elasticity of the tiles.

In Figure 11 is shown a graphic comparison between the absorption of the tiles and their value in resisting shear in the beams. The points in this diagram seem to follow a line of single curvature more closely than in either of the two preceding.

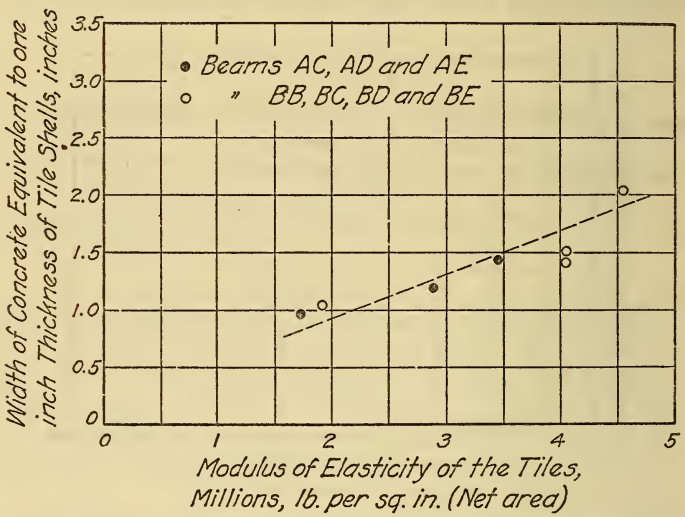

FIGURE 10.—*Relation between the modulus of elasticity of the tiles and their value (per unit thickness of shells) in resisting shear in the beams*

Similar relations could be shown between the value of the tiles and different combinations of their physical properties. In particular, there seemed to be for these data a close relation between the product of the strength and modulus of elasticity of the tiles and their resistance to shear when expressed as in Figures 9, 10, and 11. Since, however, more data would be needed to establish any definite relation which may exist for tiles in general, the classification of floor tiles on the basis of compressive strength may be justified on the grounds that such a basis is simple to apply and seems reasonable.

5. EFFECT OF THE POSITION OF THE JOINTS IN ALTERNATE ROWS OF THE TILES

Beams BC and BE were of identical construction except for the position of the joints between the tiles. In beams BC the joints between the tiles of alternate rows were staggered, while in beams

BE they were opposite. (See fig. 1.) Although the value of the tiles in the beams with staggered joints was slightly greater, the difference was small in comparison to differences in the strengths of beams of the same type of construction; and the results indicate that the position of the joints in alternate rows of tiles does not have an important effect on the assistance of the tiles in resisting shear.

6. EFFECT OF INCREASING THE NUMBER OF ROWS OF TILE BETWEEN THE CONCRETE RIBS

The type of construction represented by beams BF differed from that of the other beams in having two (instead of one) rows of tile between the concrete ribs. The strengths of these beams were not far different from the strengths of those containing only one row of tiles, but otherwise similar. By comparing the value of the tiles in beams BF with their value in the other beams (given in Table 5 and

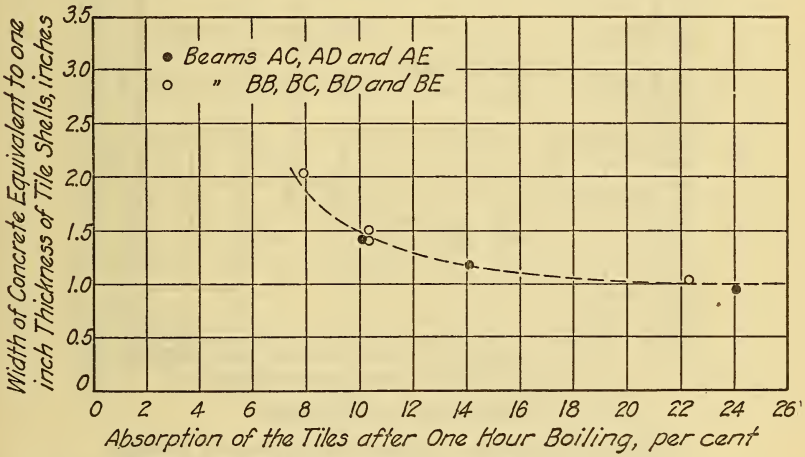

FIGURE 11.—*Relation between the absorption of the tiles and their value (per unit thickness of shells) in resisting shear in the beams*

figs. 9, 10, and 11), it is seen that an increase in the number of vertical shells and webs in beams BF ,which were not in contact with the concrete ribs, did not increase the strength appreciably. It is seen, further, that the shearing resistance of the tiles in these beams was about the same per unit of width of the shells in contact with the concrete as in other beams containingg tiles of about the same physical properties.

VI. SUMMARY OF DATA ON SHEAR TESTS OF HOLLOW TILE AND CONCRETE BEAMS

1. COMPARISONS BETWEEN THE RESULTS OF THE 1924 AND 1926 SERIES

The results of both the 1924[8] and the 1926 series indicate that the tiles assisted materially in resisting shear. A direct quantitative comparison between the values for the tiles in the two series, however,

[8] Reported in B. S. Tech. Paper No. 291.

must be somewhat uncertain because of differences in the types of specimens and the methods of testing. There is further uncertainty because some of the beams of the first series did not fail by diagonal tension.

Differences in the values for the two series, due to differences in the manner of loading and in the forms of the specimens, probably may be taken account of by comparing the strengths of the concrete beams of the same series which were similar in total dimensions and in reinforcement to the concrete ribs of the combination beams. Then, using the method described in Section V, 2, the widths of concrete equivalent, in resisting shear, to 1 inch thickness of tile shells may be found for each combination beam. Similar quantities for the 1926 series are given in Table 5 and in Figures 9, 10, and 11. For the 1924 series these widths were calculated only for the combina-

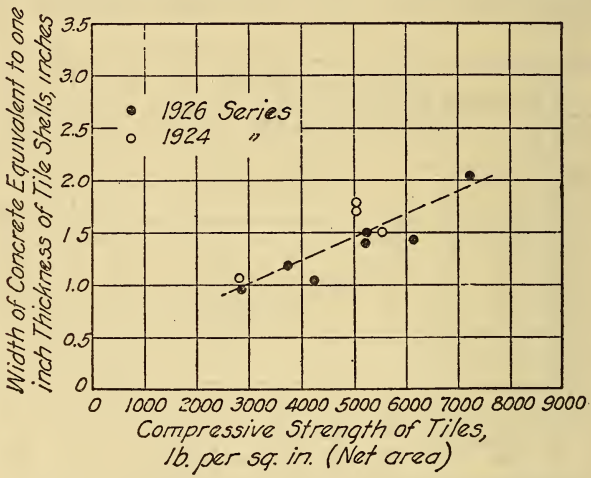

FIGURE 12.—*Relation between the compressive strength of the tiles and their value (per unit thickness of shells) in resisting shear in the beams, including results of tests made in 1924*

tion beams without a topping which were loaded in the same manner as the concrete beam B of that series.

These results for the two series are shown in Figures 12, 13, and 14. The values for the tiles when expressed in terms of equivalent widths of concrete are not widely different for the two series. There are reasons for believing, however, that the close proximity of the points for the two series is due to the combination of two influences, not yet considered in detail.

Since the values for the tiles are expressed in terms of equivalent widths of concrete, a difference in the strengths of the concrete for the two series would be expected to cause a change in the values; that is, the stronger the concrete the less width required to be equivalent to a given tile shell. Taking into consideration the proportions of the materials and curing conditions it seems safe to conclude that the concrete in the beams of the 1926 series was stronger than that in the earlier series. This influence would tend to cause the points for the 1924 series in Figures 12, 13, and 14 to lie above the

others. Some of the beams of the earlier series, however, failed in tension or in compression before they had developed their full strength in shear; and, therefore, the points lie below the positions they otherwise would occupy. It seems then that, although the widths of concrete equivalent to the tile shells in the 1924 series were about the same as in the later series, they would have been larger, owing to the difference in the strength of concrete, if the beams had been strong enough in bending to develop their full strength in shear in the tests. The data, therefore, agree with the expectation that the values of the tiles, expressed in terms of equivalent widths of concrete, would become less with an increase in the strength of the concrete.

Perhaps the chief value to be derived from the comparison between the results of the two series is the knowledge that the tiles appreciably increased the shearing strength of the beams which differed in the

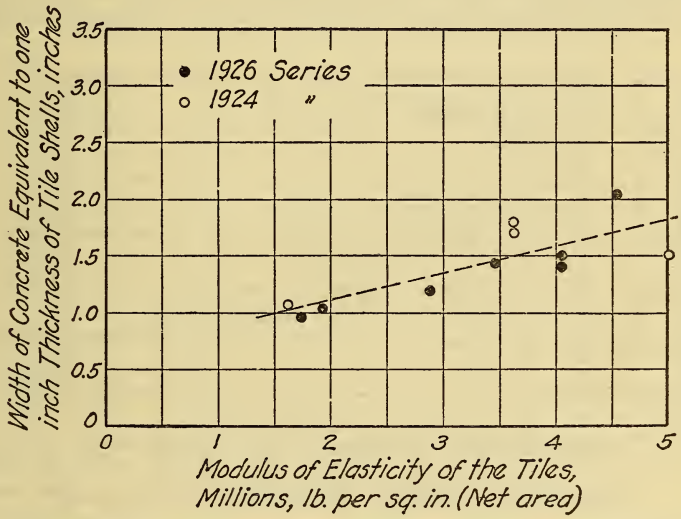

FIGURE 13.—*Relation between the modulus of elasticity of the tiles and their value (per unit thickness of shells) in resisting shear in the beams, including results of tests made in 1924*

materials used, their construction, methods of fabrication and curing. As previously noted, the specimens for the 1924 series were made by a contractor who followed methods commonly used in the construction of buildings. Those of the 1926 series were carefully made in the laboratory; the concrete was uniformly of high strength and was carefully placed so as to compact the concrete and insure its contact with the reinforcement and tiles. The fact that the tiles were effective under such widely different conditions gives confidence that the results may be applied to design.

2. APPLICATION OF RESULTS TO DESIGN

Although a discussion of working stresses and factors of safety is beyond the scope of this paper, it may be worth while to mention certain possible simplifications in the application of the results to the design of hollow tile and concrete slabs, that are not apparent from the data of the tests alone.

Usually the strength of the concrete and the physical properties of the tiles will not be known to the designer of a hollow tile and concrete slab. In general, the strength calculations for a slab will be based in part upon the assumptions: (1) The strength of the concrete will exceed a given amount, and (2) The tiles will conform to certain minimum requirements for weight and strength. In view of this it usually would not be practicable to vary the allowance for the tiles in accordance with small changes in the physical properties of the materials used in the construction. Consequently, a practical method of making an allowance for the tiles in design would be to consider the width of the section effective in resisting shear or diagonal tension equal to the width of the concrete web plus an arbitrary amount which would be the same for all tiles meeting the minimum requirements of the specification in use.

It would seem at first thought that such a rule would be grossly unjust in that all tiles would be given the same allowance regardless

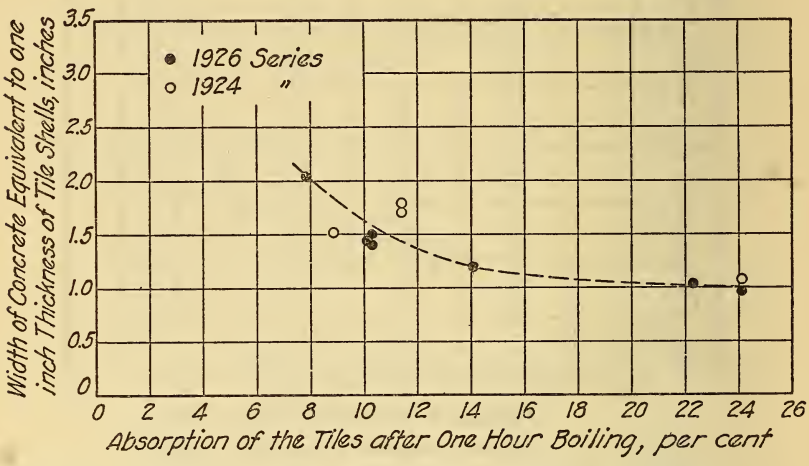

FIGURE 14.—*Relation between the absorption of the tiles and their value (per unit thickness of shells) in resisting shear in the beams, including results of tests made in 1924*

of their quality; that is, the allowance might be unduly small for tiles of medium or hard classes, and, perhaps, too large for tiles of the soft class. However, for tiles of the same size, design, and weight those classed as soft usually have thicker shells than those of the harder classes. Hence, the effect of the difference in strength on their value in resisting shear is not large, the increased shell thickness of the soft tiles compensating in part for their weaker structure. This can not be reduced to a mathematical statement because there is not a close relation between the compressive strength (net area) of hollow tile and the density of the material. There is, however, a decided tendency for a dense material to give a high strength and a low absorption (and vice versa), and Foster shows a close relation between bulk density and absorption.[9]

[9] J. Am. Ceram. Soc., **7**, No. 3; March, 1924; and Proc. Am. Soc. Test. Mats., **XXIV**, Pt. I, p. 411; 1924.

The widths of concrete equivalent in resisting shear to one row of tiles in the beams are shown in Figure 15. By comparing these values with those in Figure 9, it is seen that, while the resistance of the tiles per unit of thickness of the tile shells (fig. 9) is rather closely related to the compressive strength, the resistance of one row of tiles (fig. 15) is not greatly affected by small differences in the compressive strength. This difference is due to the fact that the tiles made of stronger material usually had thinner shells.

The results of the beam tests indicated that with tiles ranging in compressive strength (net area) from 2,870 to 7,230 lbs./in.^{2}, one row was equivalent in resisting shear to concrete webs from 1.6 to 2.4 inches in width, 6 out of the 7 values shown in Figure 15 lying between 1.6 and 2.1 inches. These values indicate that only a rough estimate of the compressive strength of the tiles is needed for making a

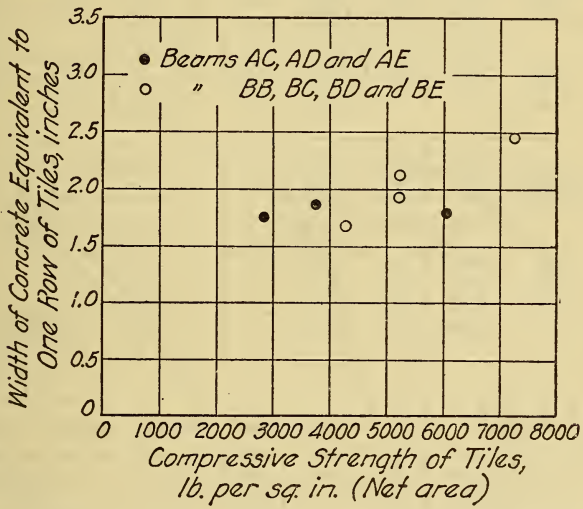

FIGURE 15.—*Relation between the compressive strength of the tiles and the value of one row in resisting shear in the beams*

fair allowance for their assistance, provided the tiles are similar in designs and weights to those tested. In selecting the allowance for tiles, the strength of the concrete should be given consideration. The values for the tiles just given were obtained with concrete, of which cylinders developed a compressive strength of 3,000 lbs./in.^{2}. As previously noted, smaller values would be expected with concrete of greater strength and larger values with concrete of lesser strength.

VII. RESULTS OF THE BEND TESTS, BEAMS OF SERIES D

1. TYPES OF FAILURES

Two of the concrete beams (DA–1 and DA–2) failed by the crushing of the concrete; and, although the third beam (DA–3) failed by diagonal tension, the measured strains in the concrete indicate that a compressive failure would have taken place with an increase in the

maximum load of not more than 5 per cent. With the exception of beams DD–2 and DE–3, all of the combination beams of series D failed in compression. For these two, the steel reinforcement had begun to yield before the maximum load had been reached.

Even though the maximum loads supported by the combination beams were about equal in many cases to the loads resisted by the concrete beams, it is seen by the graphs of Figures 16, 17, and 18 that the deformations in the concrete and reinforcement of the

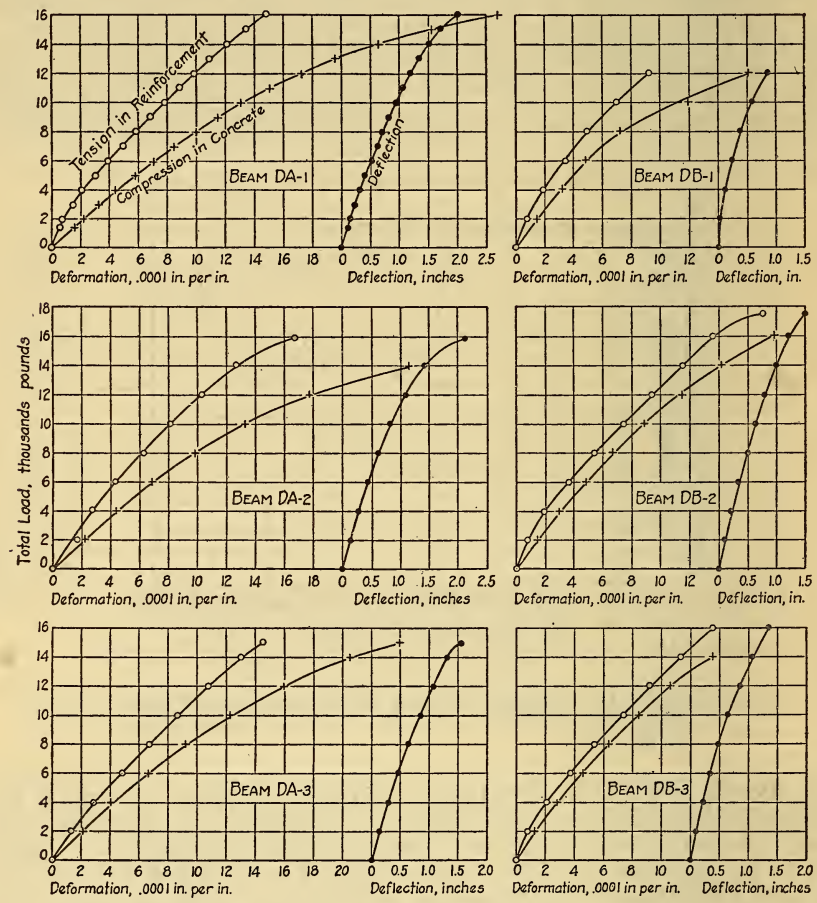

FIGURE 16.—*Load-deformation curves and load-deflection curves for beams DA and DB*

The elongations in the lower surface of the reinforcement are shown by open circles, the compressions in the upper surface of the concrete by crosses, and the deflections of the beams by filled circles.

combination beams and the deflection of these beams were markedly less than the similar values for the concrete beams. For example, the strains in the concrete and steel and the deflections of the combination beams corresponding to a load of 8,000 pounds were on the average, respectively, 70, 84, and 74 per cent of the similar values for the concrete beams. It is apparent from these values and from the curves of Figures 16, 17, and 18 that the tiles were effective in stiffening the beams.

TABLE 6.—*Series D, dimensions of beams and results of tests*

Beam No.	Lot No. of tiles in beams	Total width of tile shells in contact with concrete ribs t	Depth to steel d	Total width of concrete ribs b	Approximate load at partial failure of bond to tile	Maximum load L	Computed maximum compressive stress f_c	Type of failure
		Inches	*Inches*	*Inches*	*Pounds*	*Pounds*	*Lbs./in.*^{2}	
DA-1	(1)	--------	7.06	8.23	--------	16,000	4,775	Compressive.
DA-2	(1)	--------	7.14	8.23	--------	15,850	4,635	Do.
DA-3	(1)	--------	6.98	8.23	--------	15,500	4,720	Diagonal tension.
Average	--------	--------	7.06	8.23	--------	15,783	4,710	
DB-1	3	3.76	6.78	7.82	11,000	12,000	4,010	Compressive.
DB-2	3	3.76	6.82	7.85	16,000	17,450	5,755	Do.
DB-3	3	3.76	6.78	7.63	14,000	16,000	5,460	Do.
Average	--------	3.76	6.79	7.77	14,000	15,150	5,075	
DC-1	4	3.12	6.72	7.96	12,000	15,350	5,140	Do.
DC-2	4	3.12	6.73	8.01	12,000	16,500	5,485	Do.
DC-3	4	3.12	6.78	7.96	14,000	16,000	5,275	Do.
Average	--------	3.12	6.74	7.98	12,667	15,950	5,300	
DD-1	5, 4	3.32	6.63	8.01	14,000	17,100	5,840	Do.
DD-2	5, 4	3.32	6.68	7.81	14,000	16,950	5,830	Tensile or compressive.
DD-3	5, 4	3.32	6.63	7.98	14,000	16,700	5,720	Compressive.
Average	--------	3.32	6.65	7.93	14,000	16,917	5,797	
DE-1	5, 4	3.32	6.71	7.91	12,000	17,950	6,060	Do.
DE-2	5, 4	3.32	6.73	7.98	15,000	16,000	5,335	Do.
DE-3	5, 4	3.32	6.81	8.01	14,000	17,350	5,645	Tensile.
Average	--------	3.32	6.75	7.97	13,000	17,100	5,680	

[1] No tiles.

The effectiveness of the tiles at moderate loads was indicated qualitatively also by the measured deformations in the tiles; but it was observed that, in general, the strains in the tiles did not increase with an increase in load throughout the entire range of loading. On the contrary, the bond between the concrete and tiles in all combination beams was partially broken before reaching the maximum loads. For most of the beams the bond was sufficient to cause the strains in the tiles to increase with an increase in load until the measured strains in the upper surfaces of the concrete ribs were from 0.0010 to 0.0018 inch per inch, whereas the compressive strains in the upper surfaces of the concrete beams were in all cases greater than 0.0024 inch per inch before the maximum loads were reached. Although the final failures of the combination beams may be attributed to bending stresses, the partial failures of the bond between the concrete and tiles had occurred at loads less than the maximum, and the tiles were not as effective then as for the lower loads. In Table 6 are given the approximate loads at which the measured strains in one or more of the gage lines in the tile shells had ceased to increase with an increase in the loads.

2. STRENGTHS OF THE BEAMS

The tests of the beams of series D were planned to obtain information on the value of the tiles in increasing the resistance of the beams

to bending and to compare the strengths of beams which were similar except in either the design or the position of the tiles. Owing to the fact that the tiles had partially broken away from the concrete before bending failures had occurred, the desired comparisons can not be made from the results of the tests unless it can be assumed that the failure of the bond between the concrete and tiles is a typical phenomenon for tile and concrete beams of this type. It is believed, however,

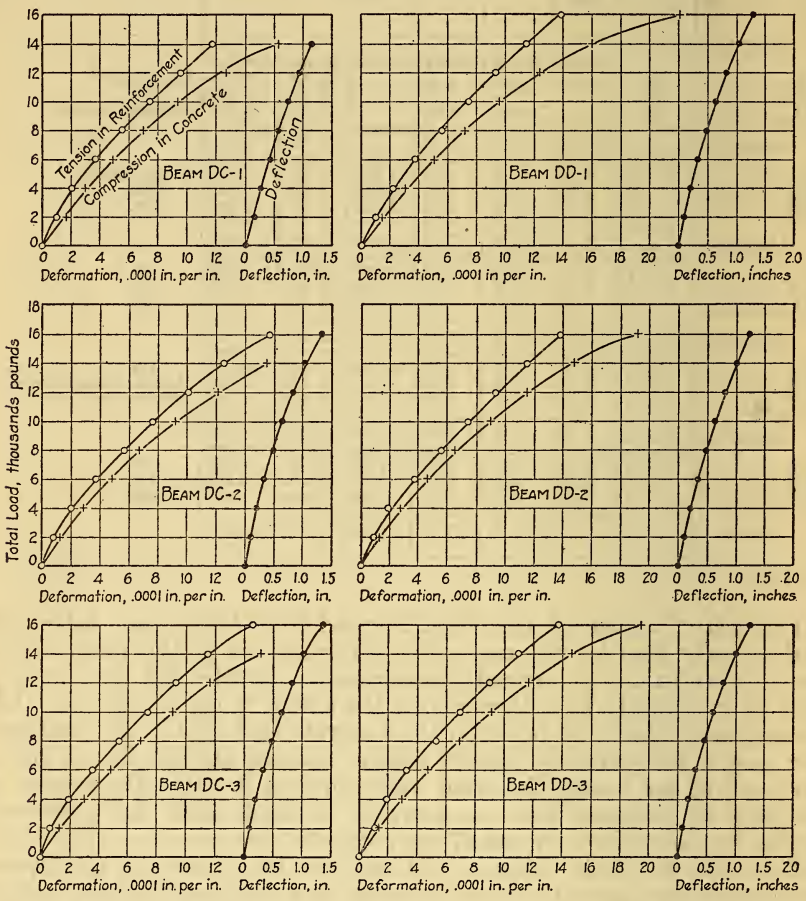

FIGURE 17.—*Load-deformation curves and load-deflection curves for beams DC and DD*

The elongations in the lower surface of the reinforcement are shown by open circles, the compressions in the upper surface of the concrete by crosses, and the deflections of the beams by filled circles.

that this is not the case, since it is shown in Section VIII that the procedures followed in construction and curing were, of those tried, the most unfavorable for developing a strong bond.

As previously noted, the tiles for the beams were thoroughly wetted, once about one-half hour before and again immediately preceding the placing of the concrete. This procedure was followed in order to prevent the absorption by the tiles of an appreciable amount of the mixing water of the concrete, which would have tended to produce a

stronger concrete in the combination beams than that in the concrete beams. By a careful proportioning of the concrete materials and by saturating the tiles and the forms it was hoped that the concrete in the beams would be of uniform strength. Damp storage was provided

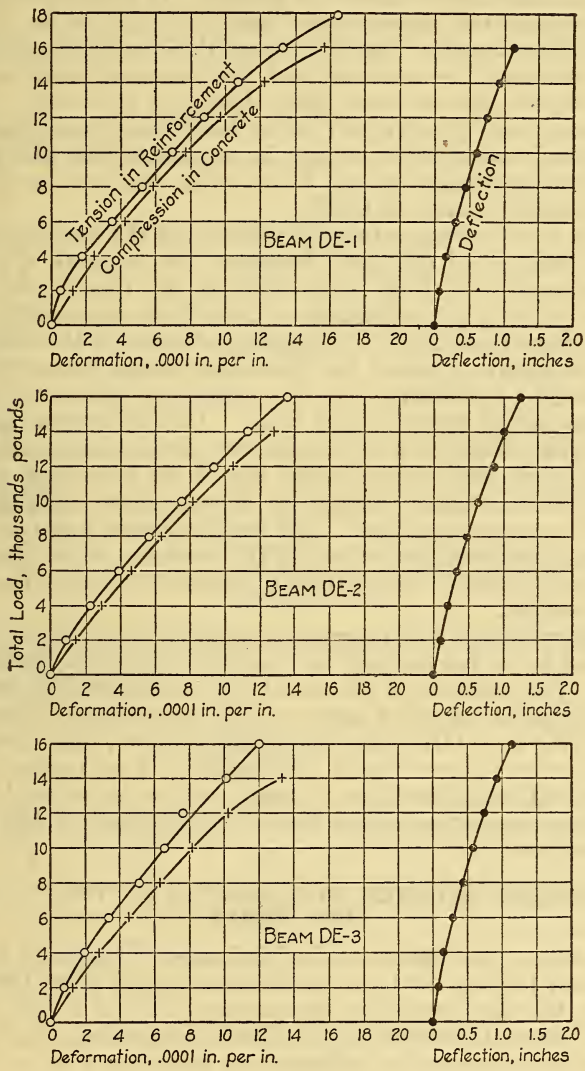

FIGURE 18.—*Load-deformation curves and load-deflection curves for beams DE*

The elongations in the lower surface of the reinforcement are shown by open circles, the compressions in the upper surface of the concrete by crosses, and the deflections of the beams by filled circles.

for the same reason; that is, to maintain more uniform curing conditions for the concrete than would have existed if beams of different sizes and forms had been permitted to dry out soon after construction. While this procedure probably was an aid in obtaining concrete of

uniform strength, it appears that it prevented the development of as strong a bond as would normally be obtained. It is shown in Section VIII that the strongest bond between concrete and hollow tile is obtained with tiles that are either dry or only moderately dampened at the time the concrete is placed. It is shown further that damp curing did not improve the bond as much as the compressive strength of the concrete. In the tests of the beams of the 1924 series [10] the bond between the concrete and tiles was sufficient to resist the tendency of the tiles to break away from the concrete. Since these earlier beams were constructed under conditions more nearly similar to commercial construction, it may be concluded that the weakness of the bond in the beams of the later series was due to the unusual construction and curing methods.

In Table 6 are given certain dimensions of the beams, the loads at which the failures of the bond between the concrete and tiles were noted, the maximum load supported by the beams and calculated quantities [11] giving an indication of the effectiveness of the tiles.

The computed maximum compressive stresses in the concrete were, with one exception, greater for the combination beams than for the concrete beams, indicating that the tiles were somewhat effective in spite of the partial failure of the bond. It is, of course, realized that the computed values for the compressive stresses corresponding to the maximum loads are greater than would be found by calculations which took into account changes in the modulus of elasticity of concrete with increases in stress. The results given, however, are based upon an assumed constant value for the modulus, since they may then be compared directly with working stresses to judge the factors of safety of designs.

The higher strengths of beams DD and DE over beams DB and DC are believed to be due entirely to the difference in the surface finish of the tiles. The surfaces of the 6-cell tiles in beams DB and DC were smooth except for rounded scores, while the surfaces of the 4-cell tiles in beams DD and DE were of rougher texture, and the grooves in these tiles were angular and dovetailed. The better mechanical bond obtained with the tiles of rough surface is probably the cause of the higher strengths rather than the difference in the number of cells in the tiles.

3. COMPARISONS BETWEEN THE RESULTS OF THE 1924 AND THE 1926 SERIES

In the tests of the beams of the 1924 series [12] the bond between the concrete and tiles seemed to remain intact until after the failures of the beams, the tiles increasing the resistance of the beams to bending. For these beams the effect of the tiles in increasing the resistance of the beams to compressive failures was equivalent to an increase in

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[10] Reported in B. S. Tech. Paper No. 291.

[11] Following the notation and formulas for rectangular beams given in the 1924 report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete (see footnote 6):

The values of the computed maximum compressive stress (f_c) were derived from the formula $f_c=\frac{2M}{kjbd^2}$ in which the bending moment (M) for a beam was equal to that at mid span due to the maximum load, and the values of b and d were, respectively, the measured total width of the concrete ribs and depth of the steel. The values of k and j were computed on the basis of $n=12$ by means of the formulas for rectangular beams of the joint committee, the only exception from the recommended procedure being that for the combination beams the ratio of reinforcement was taken as the area of reinforcement divided by the combined areas of the concrete ribs and the vertical tile shells.

[12] Reported in B. S. Tech. Paper No. 291.

the width of each concrete rib of from 2.0 to 4.5 inches, the amount for any one type of tile being approximately proportional to the product of the modulus of elasticity and the thickness of the tile shells.

The effect of the tiles on the stiffness of the beams was marked in both series. A comparison of the average of the deflections of the combination beams with similar values for the concrete beams is shown in Figure 19. For these beams (1926 series) the deflections of

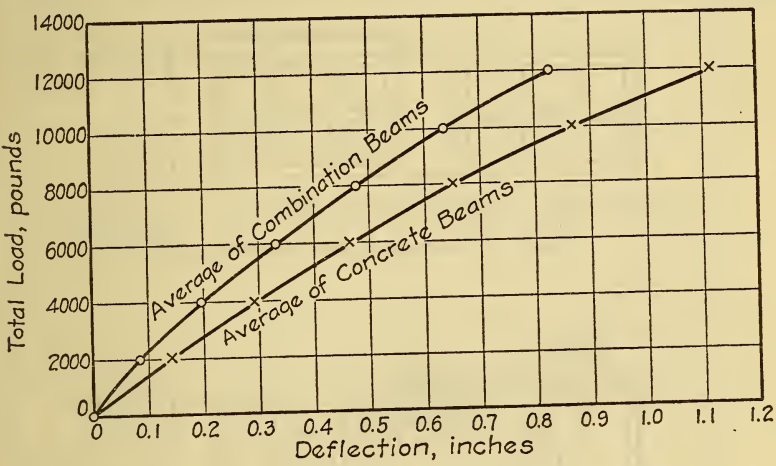

FIGURE 19.—*Average load-deflection curves for the concrete and for the combination beams*

the combination beams were, on the average, about 0.7 as great as for the concrete beams.

VIII. TESTS OF THE BOND BETWEEN CONCRETE AND HOLLOW TILE

The tests described in this section were made chiefly to obtain data which would be of assistance in interpreting the results of the tests of the series D beams. In particular, they were planned to obtain information on the effects of the following factors on the strength of the bond between concrete and hollow tile: (1) The absorption of the tiles, (2) the moisture content of the tiles at the time of placing the concrete, and (3) the proportions, consistency, and curing conditions of the concrete.

1. THE TEST SPECIMENS

(a) TYPE

As shown in Figure 20, the specimens for the bond tests resembled portions, 12 inches long and 28 inches wide, from a hollow tile and concrete slab 8 inches in depth. Each consisted of a concrete block (right prism) between two 8 by 12 by 12 inch tiles. The concrete blocks filled the 4-inch spaces between the tiles to the full depth of 8 inches. In the other direction only the central 9 inches along their length was filled. Thus 4 by 8 by 9 inch concrete blocks were formed, which were in contact over an 8 by 9 inch surface of each tile.

Although the method of producing bond stresses and the distribution of these stresses in specimens of this type differ materially from those in a slab, there are important features which are similar. In a slab the compressive strains in the concrete ribs tend to produce, through shearing bond stresses parallel to the cells of the tiles, corresponding strains in the tiles. The stresses in these test specimens which tend to break the bond are similar in nature and direction, even though their distribution is different than in a slab. Since the purpose of the tests was to compare the strengths of specimens of

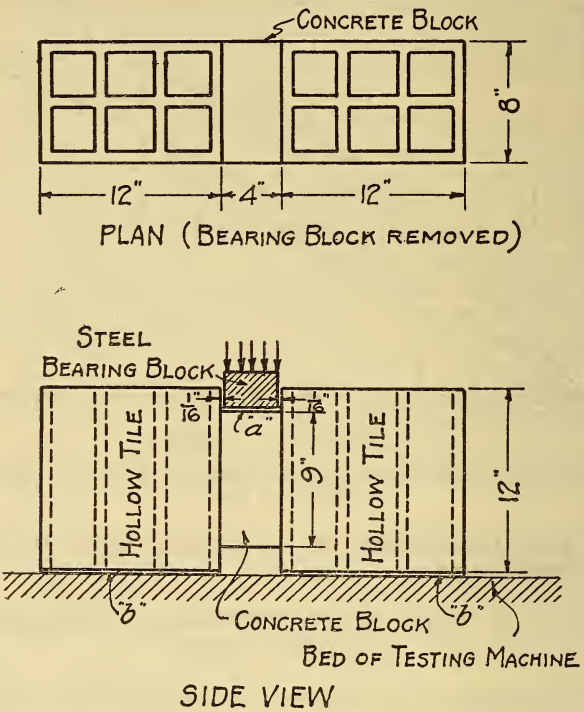

FIGURE 20.—*Details of specimens for the bond tests*

the same size and shape, but differing in materials and treatment, the absolute values obtained are not of great importance in this study.

(b) MATERIALS, CONSTRUCTION, AND AGING

The Kentucky shale tiles were of the same type and from the same plant as those of lot No. 4 used in the 1924 series of slab tests.[13] The tiles of Ohio fire clay were similar in the same way both to those of lot No. 3 of the 1924 series[13] and lot No. 1 (Table 4) of the present series, while the 6-cell and the 4-cell New Jersey fire-clay tiles were, respectively, from lots 3 and 5 (Table 4) of the present series.

The materials for the concrete were similar to those for the beams, and, except for differences in the proportions, were mixed and placed in the same manner. The mixtures listed in Table 7 were proportioned by dry rodded volumes, the proportion of sand to gravel being the same for all bond specimens.

[13] B. S. Tech. Paper No. 291, Table 3, p. 477.

TABLE 7.—*Results of the bond tests*

Reference No.	Kind of tile	Concrete			Moisture in tile before placing concrete	Water per cubic foot of wet concrete	Storage	Compressive strength 6 by 12 inch cylinder	Compressive strength of block	Ratio of block strength to cylinder strength	Bond strengths		
		Mix	Slump	Water cement ratio (w/c) by volume							Maximum	Minimum	Average of 5 tests
			Inches		*Per cent*	*Pounds*		*Lbs./in.²*	*Lbs./in.²*		*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
1	Kentucky shale	1:2:4	8	1.25	0	14.08	Dry	1,400	1,010	0.72	225	125	186
2	do	1:2:4	8	1.25	[1] 3.3	14.08	do	1,400	830	.59	270	130	177
3	Ohio fire clay	1:2:4	8	1.25	0	14.08	do	1,400	1,410	1.00	374	222	277
4	do	1:2:4	8	1.25	[1] 5.4	14.08	do	1,400	840	.60	174	83	126
5	New York surface clay	1:2:4	8	1.25	0	14.08	do	1.400	1,200	.86	318	151	256
6	do	1:2:4	8	1.25	[2] 3.7	14.08	do	1,400	1,050	.75	300	185	238
7	do	1:2:4	8	1.25	[1] 21.4	14.08	do	1,400	720	.52	183	98	138
8	New Jersey 6-cell fire clay	1:2:4	8	1.25	0	14.08	do	1,400	1,570	1.12	382	200	295
9	do	1:2:4	8	1.25	[2] 1.4	14.08	do	1,400	1,560	1.11	409	180	286
10	do	1:2:4	8	1.25	[2] 1.3	14.08	Damp	1,400	1,490	1.06	395	104	235
11	do	1:2:4	6	1.15	[2] 1.2	13.07	Dry	1,550	1,610	1.04	500	214	373
12	do	1:2:4	9	1.35	[2] 1.0	15.10	do	1,060	1,320	1.25	366	160	301
13	do	1:1.5:3	8	.98	[2] 1.5	14.22	do	2,200	1,920	.87	441	306	354
14	do	1:1.5:3	8	.98	[2] 1.6	14.22	Damp	2,200	2,110	.96	381	137	274
15	do	1:2:4	8	1.25	[2] 9.6	14.08	Dry	1,400	950	.68	278	136	190
16	New Jersey 4-cell fire clay	1:2:4	1¾	1.00	0	11.51	do	1,910	1,960	1.03	385	279	324
17	do	1:1.5:3	8¼	1.00	0	14.48	do	1,930	1,530	.79	265	177	242
18	do	1:2.5:5	3	1.25	0	11.80	do	1,400	1,760	1.26	395	255	312
19	do	1:2:4	8	1.25	0	14.08	do	1,150	1,370	1.19	234	210	245
20	do	1:2:4	1¾	1.00	0	11.51	Damp	1,910	2,000	1.05	354	247	278
21	do	1:2:4	8	1.25	0	14.08	do	1,150	1,540	1.34	333	248	288
22	do	1:1.5:3	8	1.08	[1] 9.6	14.48	do	2,050	1,600	.78	203	163	171
23	Kentucky shale	1:1.5:3	6¼	.93	0	13.57	Dry	2,300	1,760	.77	333	209	283
24	do	1:1.5:3	6¼	.93	0	13.57	Damp	2,300	2,000	.87	405	287	371

[1] Tiles immersed in water at 70° F. for 24 hours before concreting.

[2] Tiles dipped in water at 70° F. for 5 seconds before concreting.

The tiles for the bond specimens were first dried to constant weight; then, before making the bond specimens, some were dampened by dipping in water for 5 seconds, others were completely immersed in water for 24 hours, and the remainder were used without wetting. The bond specimens were made with the cells of the tiles in a horizontal position. The concrete was mixed by hand, one bond specimen and one 6 by 12 inch cylinder being made from each batch.

From 24 to 48 hours after the specimens were made they were removed from the molds and placed in storage. The 6 by 12 inch concrete cylinders were kept in damp storage until ready for testing. Some of the bond specimens were kept in damp storage until 14 days old and then were allowed to dry 14 days before testing; the others were kept in dry storage. All specimens were tested when 28 days old.

2. TESTING

Previous to testing, the bond specimens were capped, as indicated in Figure 20, with a 2:1 cement-gypsum paste on the upper surface of the concrete block (marked "*a*") and on the bearing surface of the tiles (marked "*b*"). In testing the bond specimens the tiles were supported on the base of the testing machine, and the load was applied through a spherical bearing and a machined steel block to the upper surface of the concrete block. After the concrete blocks had been broken from the tiles in the bond tests they were capped with plaster of Paris on their 4 by 8 inch surfaces and tested in compression.

For the specimens made with saturated tiles, the concrete blocks remained intact and broke away from the tiles at the contact surfaces. In the other specimens the failures were accompanied by shearing in the concrete adjacent to the tile surfaces. In a few cases the blocks were broken to such an extent that they were not suitable for compressive tests, these failures usually being caused by diagonal cracks which started at the top and extended downward at an angle of about 45° from one tile to the other. The friction between the specimen and the base of the testing machine seemed to be great enough to prevent the tiles from breaking away from the bedding during a test. The movement and deformation of the tiles were measured during the test of one bond specimen. It was found that there was compression in the entire cross sections of the tiles and that the tiles separated more at the top than at the bottom.

3. RESULTS OF THE TESTS

The details regarding the materials for the specimens and the results of the tests are given in Table 7. The New Jersey fire-clay tiles used in the bond tests were samples selected from two of the lots for the beams, the 6-cell and the 4-cell being, respectively, lots 3 and 5.

(a) EFFECT OF THE STRENGTH OF THE CONCRETE ON THE STRENGTH OF THE BOND

Figure 21 shows graphically a comparison between the compressive strength of the concrete blocks and the bond strengths. The results from the dry-cured specimens are shown by filled characters and the values for the damp-cured specimens are shown by open characters. The line shown is the graph of a linear equation which best represents the trend of the values for the dry-cured specimens, without regard

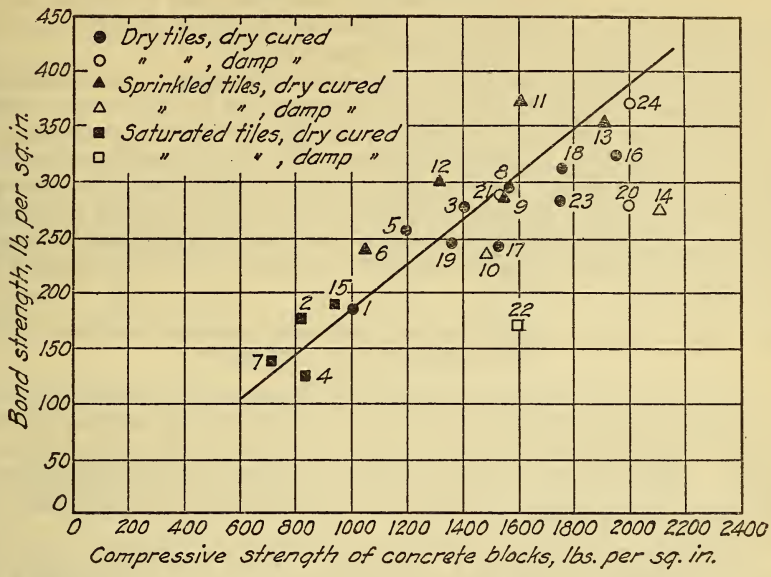

FIGURE 21.—*Relation between the bond and the compressive strength of the concrete blocks*

The numbers refer to the reference numbers given in Tables 7 and 8. The line is intended to represent the trend of values for the dry-cured specimens only.

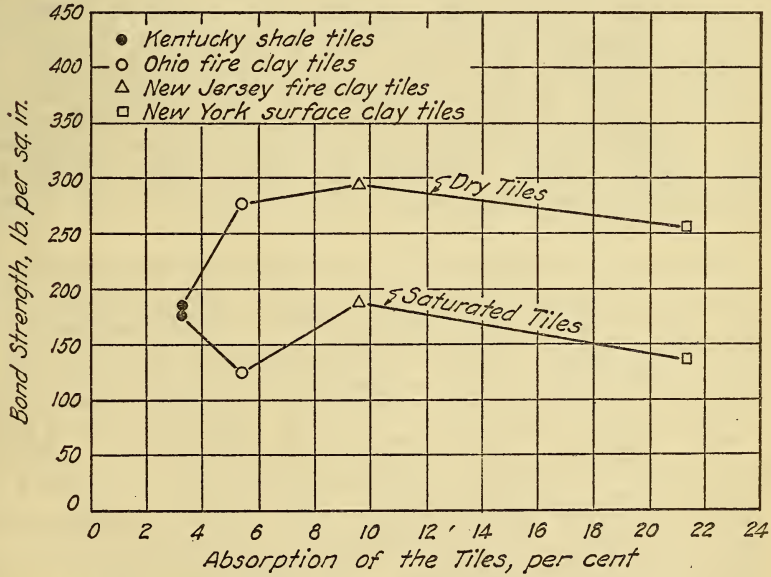

FIGURE 22.—*Effect of the absorption and the moisture content of the tiles on the bond*

The comparisons shown are confined to values from the dry-cured specimens made with 1:2:4 concrete.

for the others. Although there is a considerable scattering of the plotted points, it is seen that the bond strength usually increased with an increase in the strength of the concrete.

The bond strengths of the damp-cured specimens made with tiles of medium absorption (New Jersey) were less for the same concrete strength than the bond strengths of the dry-cured specimens. Of the damp-cured specimens with these tiles, the lowest bond strength for a corresponding concrete strength was obtained with the saturated tiles. With the tiles of low absorption (Kentucky), the relation between the bond strength and the concrete strength was not appreciably affected by either the moisture content of the tiles or the curing conditions.

(b) EFFECT OF THE ABSORPTION AND MOISTURE CONTENT OF THE TILES ON THE STRENGTH OF THE BOND

In Figure 22 is shown a comparison between the absorption of the tiles and the strength of the bond. The values for the bond strength were obtained from the dry-cured specimens made with 1:2:4 concrete. The absorption of the tiles is the weight of the water absorbed after 24 hours' immersion at 70° F. expressed as a percentage of the dry weight of the tiles.

With specimens built with saturated tiles, the strength of the bond was practically independent of the absorption. The specimens made from dry tiles having absorptions from 5 to 20 per cent did not show a wide variation in bond strength. Except with the tiles of lowest absorption, there was a material decrease in bond strength due to the tiles being saturated at the time the concrete was placed. Practically no difference in bond strength existed, however, between the dry and saturated shale tiles having an absorption of 3 per cent. The bond strengths of the three sets of specimens 5, 6, and 7 and likewise 8, 9, and 15 may be compared to determine the effect of the moisture content of the tiles at the time the concrete was placed, those in each of the two groups of three being of identical construction except for this factor. Although the strengths were markedly less with saturated tiles, they were about the same with the dipped as with the dry tiles.

(c) EFFECT OF THE CURING CONDITIONS ON THE STRENGTH OF THE BOND

Table 8 shows the comparison in bond strength between dry and damp curing. From Groups D and F it is seen that damp curing increased the bond strength of specimens made from dry tiles and comparatively wet concrete, whereas in Group E the damp curing of specimens made from a comparatively dry concrete showed a decrease in bond strength. It might be expected, therefore, that the damp-cured specimens in Groups A and B should also develop higher bond strength than those dry cured. These specimens, however, were made from dipped tiles, and damp curing resulted in lower strengths than dry curing. As shown by Group C still less bond strength was obtained with saturated tiles. The indications are that with damp curing the bond strength is less the greater the moisture content in the tile.

TABLE 8.—*Results of bond tests showing the effect of the curing conditions on the bond*

Reference No.	Group	Kind of tile	Mix	Slump	Storage	Treatment of tiles before placing concrete	Bond strength
				Inches			*Lb./in.²*
9	A	New Jersey fire clay, 6 cell	1:2:4	8	Dry	Dipped	286
10	A	do	1:2:4	8	Damp	do	235
13	B	do	1:1½:3	8	Dry	do	354
14	B	do	1:1½:3	8	Damp	do	274
22	C	New Jersey fire clay, 4 cell	1:1½:3	8	do	Saturated	177
19	D	do	1:2:4	8	Dry	Dry	245
21	D	do	1:2:4	8	Damp	do	288
16	E	do	1:2:4	1¾	Dry	do	324
20	E	do	1:2:4	1¾	Damp	do	278
23	F	Kentucky shale	1:1½:3	6¼	Dry	do	283
24	F	do	1:1½:3	6¼	Damp	do	371

(d) EFFECT OF THE PROPORTIONS OF THE CONSTITUENTS OF THE CONCRETE ON THE STRENGTHS OF THE CONCRETE CYLINDERS AND BLOCKS

It was shown by Figure 21 that, in general, the strength of the bond increased with an increase in the strength of the concrete blocks between the tiles. The strength of the concrete cylinders, made and cured by the methods commonly employed for control specimens of this type, may be taken as measures of the quality of the concrete mixtures used in the bond specimens. Since, however, there was neither a close relation between the strengths of the cylinders and the blocks made from the same mixes nor between the strengths of the cylinders and the bond strengths, it would be of value to determine, if possible, the factors which caused the large variations in the relation between the strengths of the cylinders and the blocks. For the present purposes it is not necessary to include in this study the effects of such factors as the form of test specimen and curing conditions, since we are not concerned because the strengths are different, but only because the strengths of the two different specimens are not related.

It has been shown that the strengths of concrete cylinders made from the same cement, and with the same type and grading of aggregates, and by the same process are closely related to the ratios of the volumes of water and cement (water-cement ratio) in the mixes.[14] With concrete cast in nonabsorptive forms the water-cement ratio of the mix may be calculated readily when the amount of each ingredient and the absorption of the aggregate are known. When, however, concrete is molded in porous forms, such as hollow tiles, some of the mixing water is absorbed and the effective water-cement ratio is less than the values so calculated. With concretes having such workable properties that they may be compacted in the forms, a reduction in the water-cement ratio may be expected to cause an increase in the strength of the resulting concrete. It would be expected, further, that the effect of the absorption of the tiles on the water-cement ratios, and consequently on the strength of the concrete blocks, would be most pronounced with the mixes containing the least amount of water, since with a given absorption the less the amount of water present in the mix the greater the percentage reduction.

[14] Abrams, Bulletin No. 1, Lewis Institute, Chicago, Ill.

In Figure 23 values from the dry-cured specimens made with dry and dipped New Jersey fire-clay tiles are shown graphically to illustrate the effect of the amount of water in the batches on the ratios between the strengths of the cylinders and the block. The values for the water-cement ratio of the concrete as mixed are shown adjacent to the plotted points. Dashed lines sloping upward to the left were drawn empirically to represent contours of equal water-cement ratios. The leaner mixes are at the upper portions of the curves. It is seen from Figure 23 that the ratio of block strength to cylinder strength increased as the water-cement ratio increased and as the amount of water in the batch decreased. The ratio of block strength was greatest,

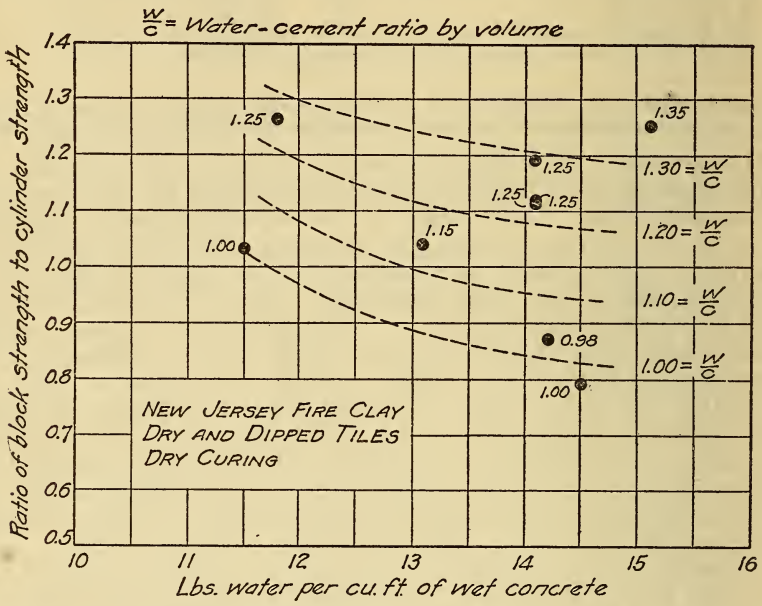

FIGURE 23.—*Relation between the amount of mixing water and the ratio of block strength to cylinder strength*

therefore, with lean concrete mixtures of comparatively dry consistency. These conclusions obviously would be different with specimens consisting of a thin bed of mortar or concrete in contact with absorptive forms.

4. CONCLUSIONS

In general, the results of these tests indicate that the strength in shear of the bond between hollow tiles and concrete was greatest when concrete containing the minimum amount of water necessary for its proper placement was used in combination with dry or dipped tiles of medium absorption. Some of the concrete mixtures used in the test specimens probably were of drier consistency than could be placed properly in commercial construction, and for this reason the apparent advantage of the driest mixtures might not be realized in practice.

In particular it may be stated that—

1. For dry-cured specimens the bond strength in shear increased with the strength of the concrete blocks between the tiles.

2. For specimens made from dry tiles the bond strength in shear did not vary widely with tiles having absorptions between 5 and 20 per cent.

3. With tiles having absorptions between 5 and 20 per cent, the bond strength in shear was markedly less for specimens made with saturated tiles than with those made with dry or dipped tiles.

4. Except with specimens made with dry tiles and concrete of wet consistency (slumps 6¼ and 8 inches), the bond strengths in shear were greater for the dry-cured than for the damp-cured specimens.

5. For specimens made from New Jersey fire-clay tiles the ratio between the strengths of the concrete blocks and the cylinders increased as the water-cement ratio increased and as the amount of water in batch decreased.

In order to judge whether the methods followed in the construction of the beams of series D were favorable or unfavorable to the development of a strong bond between the concrete and hollow tile, the factors pertaining to the beams, which were found in the bond tests to affect the bond, may be recalled. They may be summarized as follows:

1. The tiles were of medium absorption (New Jersey clay) and were thoroughly wetted before the concrete was placed.

2. The beams were kept in damp storage for 28 days and were then kept in dry storage for 2 weeks before testing.

3. The concrete for the beams was of wet consistency. The average slump of the concrete was 9.4 inches; the water-cement ratio was 1.00; and the mixes contained 18 pounds of water per cubic foot of concrete.

Comparing these factors with the results of the bond tests, it is seen that the wetting of the tiles and the damp curing of the beams were unfavorable to the development of strong bond. Since, however, the tiles were wet when the concrete was placed, the effect of the amount of mixing water in the concrete on the absorption of the water by the tiles was not important.

Washington, August 28, 1929.