Properties of Cavity Walls

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[List continued on cover page III]

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Properties of Cavity Walls

Daniel S. Goalwin

Building Materials and Structures Report 136

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Contents

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A compilation is given of data on the performance characteristics of cavity walls, including previously published and some hitherto unplublished material. Structural tests were conducted on cavity walls of brick, concrete block, and structural clay tile. Other tests were made on the properties of wall ties, rain penetrability, thermal transmittance, and fire resistance.

Under certain conditions of loading, compressive strength, resistance to concentrated load, racking load, and impact strength were found to be roughly equivalent to those of conventional walls using the same quantity and quality of material. With respect to resistence to transverse load, the cavity walls were somewhat inferior. When properly flashed and with suitable weep holes, the cavity walls had satisfactory resistance to rain penetration. Their thermal transmittance was about 25 percent lower than for similar solid walls. Their resistance to the effect of fire was satisfactory provided certain limiting loading conditions were met.

1. Introduction

A cavity wall is a form of masonry wall construction consisting of two parallel wythes [1] of masonry separated by a continuous air space, or cavity, usually about 2 in. wide. It is a type of construction that has been widely used in Great Britain for many years, and which in recent years has come into greater use in this country. Cavity walls may be constructed of various combinations and thicknesses of brick, stone, structural clay tile, concrete masonry, concrete, etc.

One of the advantages claimed for the cavity-wall construction is that the air space acts to prevent rain or moisture that has seeped through the outer wythe from penetrating the inner wythe. In addition, the cavity interrupts the continuity of the masonry and provides the additional insulating effect of an air space. These advantages may be lost by improper design of cavity walls, particularly with respect to such items as flashings, openings, ties, and wall intersections, or lack of care in construction.

Common practice at present is to distinguish between hollow and cavity walls. Hollow walls are walls that contain masonry bonds or bridges; these may permit the passage of water between the faces of the walls. In properly built cavity walls, there is no masonry bridge permitted between the outer and interior wythes, the two tiers being bonded by means of metallic or other nonmasonry ties to maintain a substantially constant cavity width. These ties are usually rods or wires bent into Z or rectangular shapes, affording anchorage by embedment of the ends in mortar joints.

Water that penetrates the outer leaf of a cavity wall seeps down its inner face and is diverted outward by means of flashings, generally placed near the bottom of the cavity and above windows and other openings, allowing the water to pass through weep holes in the outer face. These holes, while necessary to dispose of water, should be kept small so as to exclude rodents and to prevent any substantial circulation of air in the cavity, with consequent increase in thermal transmittance.

Tests of structural properties, fire resistance, heat transfer, and water resistance of cavity walls have been made at the National Bureau of Standards; most of these tests have been described in reports of the Building Materials and Structures series. It is the purpose of this report to collect both previously published and hitherto unpublished data so as to summarize in one report information on cavity walls required for building design, construction, and code proparation.

2. Cavity-Wall Design

Design criteria for cavity walls may be found in various reference works, including those of Fitzmaurice, "Principles of Modern Building" [1],[2] Plummer, "Brick and Tile Engineering" [2], and "Tile Engineering" [3]. Design of the walls tested followed closely the general requirements for cavity walls of the "American Standard Building Code Requirements for Masonry" [4], which is now in the process of revision. Sound engineering practice requires that the compressive stresses in cavity walls shall not exceed those given in table 1. These compressive stresses are based upon the gross cross-sectional area of the wall, minus the area of the cavity between the wythes, with the assumption that the floor loads bear on but one of the two wythes. When such walls are loaded uniformly at the center of the wall, the allowable

[1] The terms "wythe" and "leaf" are used interchangeably.

[2] Figures in brackets indicate the literature references at the end of this paper.

stresses may be increased by 25 percent. When anticipated wind pressures exceed 20 lb/ft^2, type B mortar should not be used on cavity walls of 12-in. thickness or less.

TABLE 1. *Maximum loading for masonry cavity walls*

Material	Allowable compressive stress (on gross less cavity area, load bearing on only one wythe).	
	Type A-1 mortar [1]	Type B mortar [1]
	lb/in.^{2}	*lb/in.*^{2}
Solid masonry units:		
Strength greater than 2,500 lb/in.^{2}	140	110
Strength 1,500 to 2,500 lb/in.^{2}	100	80
Hollow masonry units	70	55

[1] The mortar designations used in this paper are similar to those in the tentative ASTM Specifications for Mortar for Unit Masonry [7]. Mortar A-1 is defined as consisting of 1 part of portland cement by volume, ¼ part of hydrated lime or lime putty, and aggregate in amount not less than 2¼ nor more than 3 times the sum of the volumes of the cement and lime used. Mortar B consists of 1 part of portland cement by volume, not less than ½ nor more than 1¼ parts of hydrated lime or lime putty, and aggregate in amount not less than 2¼ nor more than 3 times the sum of the volumes of the cement and lime used.

ASTM C270–51T requires that the average wet compressive strength of 2-in. cubes of the mortar at 28 days be not less than 2,500 lb/in.^{2} for type A-1 and 750 lb/in.^{2} for type B.

Cavity walls should not exceed 35 ft in height, except that 10-in. cavity walls should not exceed 25 ft in height above their support. As cavity-wall floor loads are usually carried by the inner wythe, the outer wythe is customarily 4 in. in nominal thickness, and the thickness of the inner tier is increased if needed for high walls or to support heavy loads. A nominal 10-in. cavity wall consists of two nominal 4-in. leaves and a 2-in. cavity; a nominal 14-in. cavity wall consists of a 4-in. outer leaf, a 2-in. cavity, and an 8-in. inner leaf.

The facing and backing of cavity walls should be bonded with $\frac{3}{16}$-in.-diameter steel rods or metal ties of equivalent thickness embedded in the horizontal joints. The ties shall be spaced uniformly to provide at least one per 4½ sq ft of wall surface; the distance between adjacent ties should not exceed 26 in. Rods bent to rectangular shape should be used with hollow masonry units laid with cells vertical; in other walls the ends of the ties should be bent to 90-degree angles to provide hooks not less than 2 in. long. Additional bonding ties should be provided at all openings, spaced not more than 3 ft apart around the perimeter and within 12 in. of the opening. Ties should be of corrosion-resistant metal or coated with a corrosion-resistant metal or other approved protective coating.

British specifications [5] require that steel wall ties be coated with zinc. They also require a crimp or dip in the ties so as to prevent water traveling across the tie to the inner wythe. If no crimp is used, the tie should be inclined downward to the outer wythe.

Because one of the purposes of the cavity is to provide a barrier against the penetration of moisture, it is essential to provide flashing wherever the cavity has been bridged for any purpose, such as heads and jambs of openings, joist bearing points, etc.

Proper drainage should be provided at the base of the cavity to dispose of any water that might penetrate into the cavity. This may be accomplished by providing weep holes in the vertical joints of the course of masonry of the outer tier immediately above a flashing. The cavity must be kept clear of mortar droppings so that the weep holes are not obstructed and so that moisture cannot be transmitted across the cavity on a bridging of mortar.

3. Materials

Tests were conducted at the National Bureau of Standards BMS101 [6] on the strength of wall ties under axial, tensile, and compressive load, and on the corrosion resistance of steel ties coated with various materials.

Table 2 lists the basic dimensions of some of the ties, partial results of compressive tests on tie assemblies, and which tie types were used in wall specimens for other tests described later in this report. Some of the ties are shown in figure 1. Outdoor-weathering specimens are shown in figure 2.

The tensile specimens failed by pulling out of the tie, by tension failure in the tie, or by crushing of the mortar under the tie, with subsequent splitting of the brick-mortar assembly. Partial bond failure of the tie occurred in many specimens that failed in tension or by crushing of the mortar, the ends of the ties often having slipped in the bed as much as ⅛ in. The compressive-strength specimens failed either by buckling of the ties or

TABLE 2. *Properties of typical wall ties*

Kind of material	Over-all dimensions			Shape	Maximum compressive load [1]		Used in walls
	Length	Width	Thickness		Mortar A-1	Mortar B	
	in.	*in.*	*in.*		*lb.*	*lb.*	
Copperweld	6	6	0.027	Z-shape	3,880	2,180	2E.
Steel [2]	6	6	.188	do	2,025	1,810	
Do.[2]	6	6	.131	do	600	520	
Do.[2]	6	4	.158	Rectangular	2,310	2,060	
Do	6	6	.188	Z-shape			1C, 2A, 2B, 2C, 2D, 2E, 3A, 3B, 3C, 3D.
Do	6	4	.250	Rectangular			1A, 1B, 1D, 1E.

[1] Average values were obtained from tests on groups of 5 like specimens. Compressive strengths of mortars: A-1, 4,450 lb/in.^{2}; B, 1,330 lb/in.^{2}.
[2] Average yield strength of steel wires 86,000 lb/in.^{2}, the average tensile strength 90,000 lb/in.^{2}.

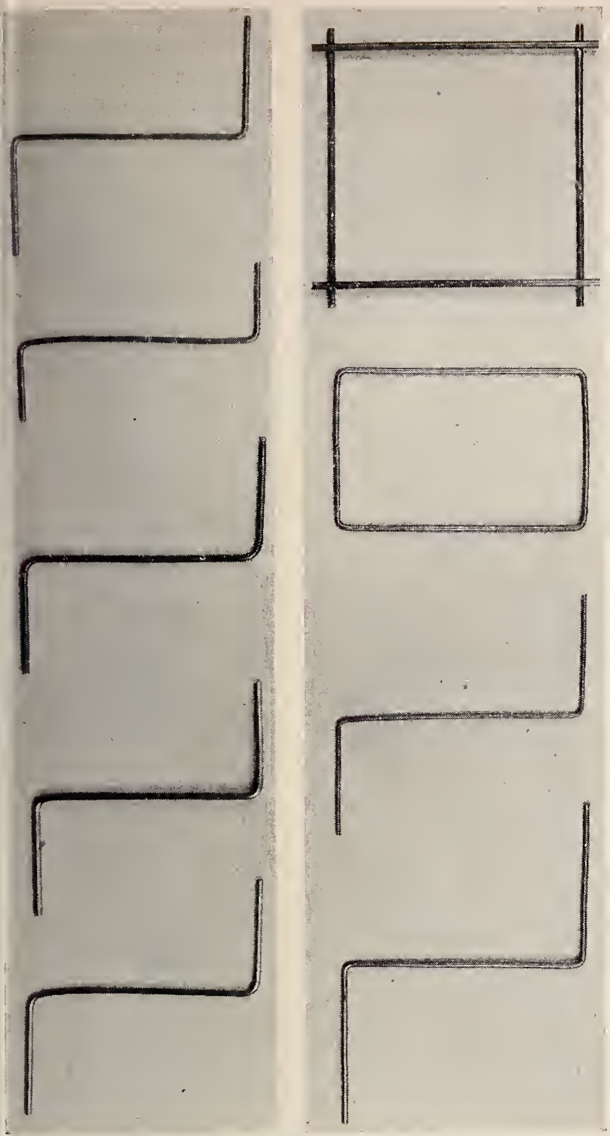

Figure 1. *Typical cavity wall ties.*

Figure 2. *Specimens for outdoor weathering of ties.*

by crushing of the mortar against the ends of the ties.

Uncoated steel ties and those coated with neat cement or mortar were lightly rusted in 10 days or less of indoor (accelerated) weathering, and most were severely rusted in 30 days. Cementitious coatings did not retard rust formation and even appeared to have had an accelerating effect. Coatings of coal-tar paint afforded some protection, but within 120 days the ties were severely rusted adjacent to the masonry. It is possible that the coatings at these points were nicked with the trowel when the mortar protruding from the joints was cut away. The copper coatings on the copperweld ties were darkened by the exposure, but no evidence of rusting of the steel beneath the copper was noted.

Uncoated steel ties corroded in less time when exposed to outdoor than to indoor (accelerated) weathering. The cementitious coatings seemed to offer better protection to the ties when exposed outdoors than indoors. Ties coated with paint were moderately rusted at points adjacent to the inner faces of the masonry after 180 days of exposure.

Physical properties of the concrete blocks, brick, and tile used in tests described later in this report are listed in table 3. Details of the con-

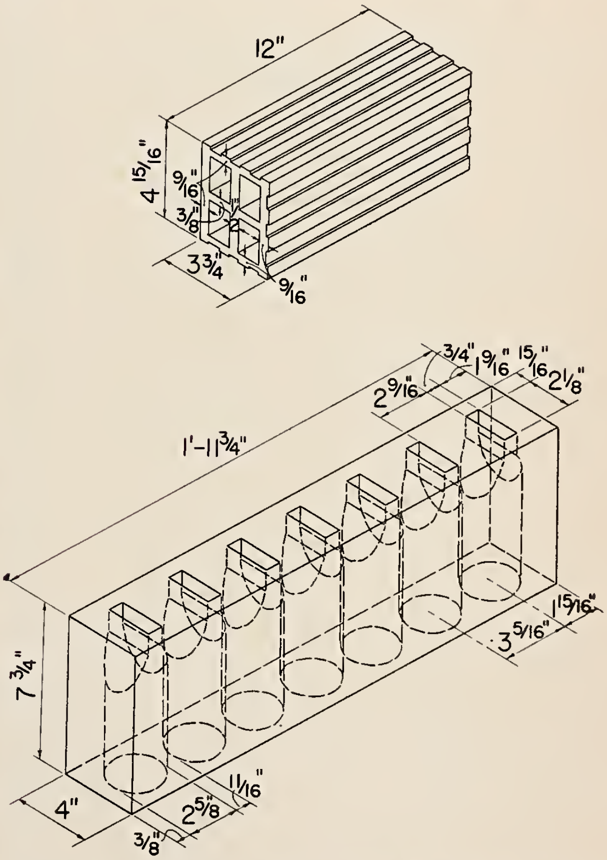

Figure 3. *Details of concrete-block and structural clay tile.*

The above include all test specimens except those used in fire-endurance tests.

TABLE 3. *Physical properties of the masonry units used in the cavity walls*

Concrete blocks

Used in walls	Dimensions	Dry weight	Aggregate	Density of concrete	Water absorption (24-hour cold immersion) By weight	Water absorption (24-hour cold immersion) By volume of concrete	Compressive strength (gross area)
	in.	*lb/block*		*lb/ft*³	*Percent*	*lb/ft*³	*lb/in.*²
1A, 1B, 1C, 1D, parts 1E-1, 1E-2	4.0 by 23.8 by 7.9	22	Cinders	88	14.4	12.7	900
Part 1E-1	4.0 by 23.8 by 7.9	31	Expanded slag	108	10.2	11.1	895
Part 1E-2	4.0 by 23.8 by 7.9	33	Sand and gravel	130	6.5	8.4	860

Brick

Used in walls	Dimensions	Dry weight	Water absorption 5-hour boil	Water absorption Saturation coefficient [1]	Water absorption Initial rate of absorption [2]	Modulus of rupture	Compressive strength
	in.	*lb/brick*	*Percent*		*oz*	*lb/in.*²	*lb/in.*²
2A, 2B, 2C, 2D	8.1 by 3.6 by 2.3	4.1	18.7	0.74	1.5	540	3,240
3A, 3B, 3C, 3D	8.0 by 3.8 by 2.3	4.8	14.7	.69	1.4	830	5,160
2E	8.0 by 3.6 by 2.2	------	20.0	.79	------------	450	3,580

Tile

Used in walls	Dimensions	Dry weight	Cells per tile	Thickness of face shell (minimum)	Ratio, width of cell to thickness of bearing shell	Water absorption (1-hr boil)	Compressive strength (load applied to side)
	in.	*lb/tile*		*in.*		*Percent*	*lb/in.*²
3A, 3B, 3D	3.8 by 4.9 by 12.0	9.5	4	0.4	2	5.9	1,720
4A-1	3.8 by 12.0 by 12.0	17.2	3	.5	5	10.2	1,040
4A-2	3.8 by 5.0 by 12.0	8.6	2	.5	5	10.7	860

[1] 24-hr cold ÷ 5-hr boil.
[2] Gain in weight of dry brick (30 in.²) in contact with ⅛ in. of water for 1 minute.

crete block and structural clay tile (except the tile used for fire-endurance tests) are shown in figure 3. The blocks were laid with the cells vertical.

Only cement-lime mortars were used in the constructions described in this report. Definitions of the classes of mortar are taken from the ASTM Tentative Specifications for Mortar for Unit Masonry, C270–51T [7], and are given in table 1. Mortar B is the familiar 1:1:6 by volume. The amount of water added to the mortar was in each case adjusted to the satisfaction of the mason.

4. Construction of Walls

4.1. Workmanship

The walls tested fall into two general classes with respect to workmanship. Workmanship A was superior to the commercial workmanship designated as workmanship B. In workmanship A, the head or cross joints were filled solidly. In workmanship B, the mortar was applied only to the outer edges of the head or cross joints. In both workmanships, a wood strip was placed on the ties to prevent mortar droppings from fouling the ties or the weep holes.

The effect of workmanship on compressive strength of brick walls other than cavity walls is discussed in "Compressive Strength of Clay Brick Walls" [8] and on transverse strength and water permeability in "Watertightness and Transverse Strength of Masonry Walls" [9].

4.2. Construction Details

Four wall types have been tested at the National Bureau of Standards, concrete-block walls, all-brick walls, walls with brick facing and clay-tile backing, and walls with structural clay tile for both facing and backing.

Details of construction, including size, mortar, and workmanship, are given in table 4. A brick-tile wall under construction is shown in figure 4.

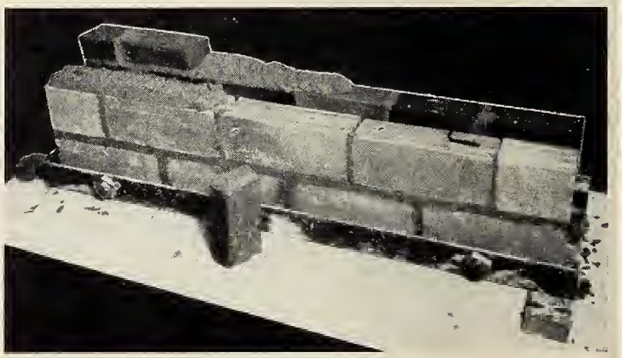

FIGURE 4. *A brick-tile cavity wall under construction for use in structural tests.*

Table 4. *Construction details of the test walls*

Wall No.	Type of wall	Type of tests	Reference		Nominal sizes of walls			Mortar [1]	Workmanship [2]
			Report	Wall designation	Width	Height	Thickness		
					ft.	*ft.*	*in.*		
1A	Cinder-concrete block.	Compressive, transverse, impact.	BMS21	AX-C, AX-T, AX-I	4	8	10	A-1	B.
1B	do	Racking	BMS21	AX-R	8	8	10	A-1	B.
1C	do	Water permeability	BMS82	B123	3	4	10	A-1	B.
1D	do	Heat transfer	(3)	HT-47	5	8	10¾	A-1	B.
1E-1	Concrete block [4]	Fire resistance	BMS117	12	16	11	10	B	B.
1E-2	do [5]	do	BMS120	3	16	11	10	B	B.
2A	Brick	Compressive, transverse, impact.	BMS23	BD-C, BD-T, BD-I	4	8	9⅝	B	A.
2B	do	Racking	BMS23	BD-R	8	8	9⅝	B	A.
2C	do	Water permeability	BMS82	B169	3	4	9⅝	B	A.
2D-S	Brick (solid)	Heat transfer	(3)	HT-23	5	8	8	B	A.
2D	Brick	do	(3)	HT-24	5	8	9⅝	B	A.
2E	do	Fire resistance	(3)	74, 75, 76	16	10	9¼	B	
3A	Brick-tile [6]	Compressive, transverse, impact.	BMS24	AU-C, AU-T, AU-I	4	8	9¾	B	A (brick), B (tile).
3B	do [6]	Racking	BMS24	AU-R	8	8	9¾	B	A (brick), B (tile).
3C	do [6]	Water permeability	BMS82	B124, B271, B272	3	4	9¾	B	A (brick), B (tile).
3D	do [6]	Heat transfer	(3)	None	5	8	9¾	B	A (brick), B (tile).
4A	Hollow tile	Fire resistance	RP37	110, 111	8	10	10	(7)	B.

[1] Definitions of mortars given in table 1. Mortar B was 1:1:6 by volume. Mortar A-1 strength at 28 days exceeded 2500 lb/in.². Mortar B strength at 28 days exceeded 750 lb/in.².
[2] Workmanship A was superior, bead joints filled. Workmanship B was commercial, head joints buttered at the edges only.
[3] From unpublished data.
[4] This wall was divided into two 8- by 11-ft sections; one section of cinder units, one section of sand and gravel units.
[5] This wall was divided into two 8- by 11-ft sections; one section of cinder units, one section of foamed-slag units.
[6] Brick facing, tile backing.
[7] 1:1:4 by volume. Strength at 60 days, 1,065 lb/in.².

The concrete-block walls tested for fire endurance consisted of two 8- by 11-ft sections each, separated by a ¾-in. air space, with blocks having different aggregates in each section. The units of one section of wall 1E-1 contained cinder aggregates, the other sand and gravel aggregates; one section of wall 1E-2 also contained cinder aggregates, the other foamed-slag aggregates.

For the walls used in the heat-transfer tests, the edges of the cavity were closed by strips of lumber and plastered over with mortar.

No finish was applied to the faces of any of the walls used in the structural or rain-penetrability tests. The concrete-block wall 1D tested for thermal transmittance had two coats of portland cement-base paint on the outside face and three coats of plaster applied directly over the inside face of the concrete blocks. The two structural clay-tile walls, 4A and 4B, tested for fire resistance, had ¾ in. of gypsum plaster on the exposed face and 1:3 portland-cement plaster plus 15 percent of lime on the unexposed face.

Ties were placed approximately 24 in. apart on horizontal centers in alternate bed joints for the concrete-block walls used in the structural, rain penetration, and fire-endurance tests, and in every third joint for the cinder-concrete block wall, 1D, used in the heat-transfer tests. They were placed in every sixth brick course for the brick and brick-tile walls.

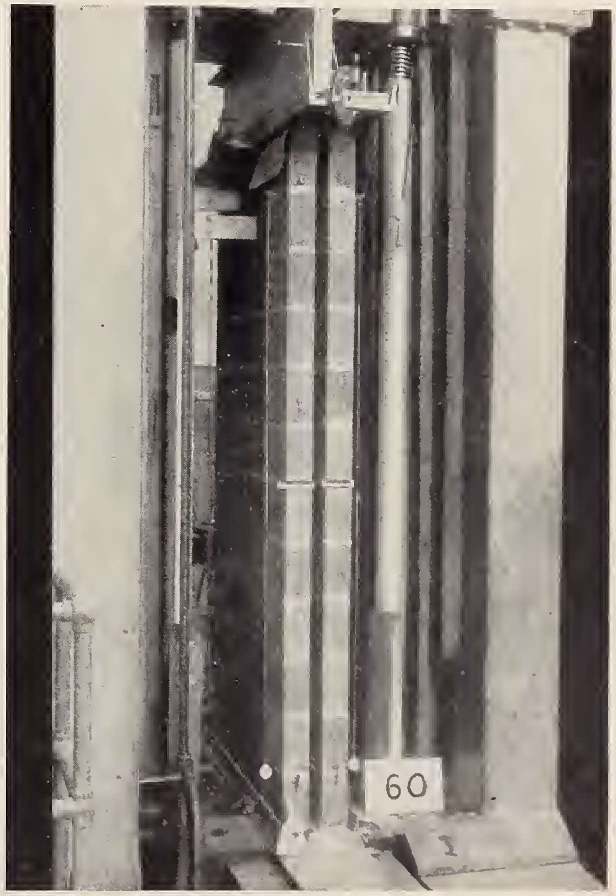

Figure 5. *Concrete-block cavity wall under compressive load.*
Load was applied through a round steel bar above beam (not visible).

5. Structural Properties

The kinds of loads encountered on exterior walls and a detailed analysis of engineering principles for the design of small houses are discussed in BMS109 [10].

Three types of cavity walls were subjected to compressive, transverse, concentrated, impact, and racking loads at the National Bureau of Standards in accordance with the procedures and methods outlined in ASTM Standard E72–47T and given in BMS2 [11]; these tests are described in detail in BMS21 [12], BMS23 [13], and BMS24 [14]. At least three wall specimens were included in each test group. In general, test procedure was to apply the load in increments, recording the deflection, then release the load and record the set.

5.1. Compressive Load

With one exception, compressive loads were applied to a steel plate covering the upper end of the specimen. The load was applied uniformly along a line parallel to the inside face and one-third the thickness of the specimen from the inside face. For one set of tests on a brick cavity wall, 2A, the load was applied to one wythe only.

A wall under compressive load is shown in figure 5; data obtained from the compressive-load tests are listed in table 5 and presented graphically in figures 6 and 7.

Failure of the concrete-block cavity walls occurred by crushing of the blocks in the back wythe in one or more courses near the top of each of the specimens. Two of the brick cavity walls failed by crushing of the brick and mortar-bed joints in two or three courses of the back wythe at about two-thirds the height, followed by rupture of both backing and face tiers at this height; one specimen failed by crushing of a few bricks and a mortar bed

Table 5. *Results of structural tests*

Figures are averages for three specimens.

Wall types	Mortar	Workmanship [1]	Compressive tests: Distance load applied from inside face	Compressive tests: Maximum load	Compressive tests: Maximum stress [2]	Transverse tests (equivalent maximum load)	Impact (maximum height of drop of 60-lb sandbag)	Racking (maximum thrust [3])	Racking modulus
			in.	*lb/lin ft*	*lb/in.²*	*lb/ft ²*	*ft*	*lb/lin ft*	*lb/ft. ²*
Cinder-concrete block walls 1A and 1B.	1–A	B	3.33	37,800	394	49.8	3.0	6,010	18.2×10⁶
Brick walls 2A and 2B	B	A	3.12	62,100	650	25.3	2.8	5,660	12.7
Brick walls 2A	B	A	(4)	50,600	528				
Brick-tile walls 3A and 3B.	B	A-brick; B-tile	3.25	27,800	290	21.5 (inside face)	3.7 (inside face)	5,160	19.3
Brick-tile walls 3A	B	A-brick; B-tile				29.1 (outside face)	3.0 (outside face)		

[1] Workmanship A, superior. Workmanship B, commercial.
[2] On net area, that is, total area less area of cavity.
[3] Thrust applied near upper corner.
[4] Load applied and centered on back wythe only.

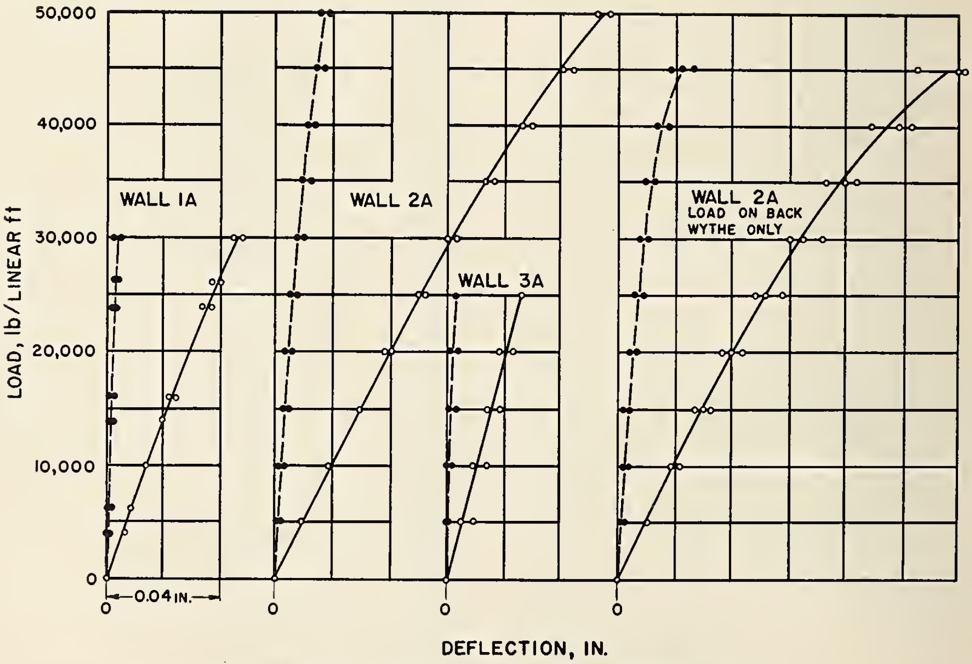

Figure 6. *Wall shortening under compressive loads.*

Opening circles represent shortenings, closed circles sets after removal of the corresponding load. Wall 1A, concrete-block cavity wall; wall 2A, brick cavity wall; wall 3A, brick-tile cavity wall.

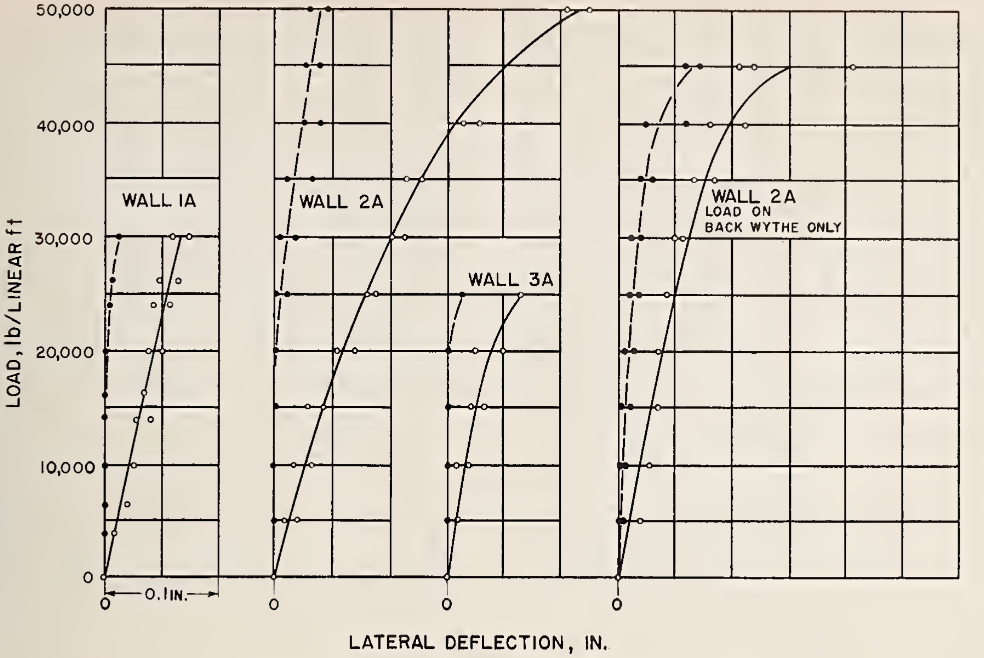

FIGURE 7. *Lateral wall deflections under compressive loads.*

Open circles represent lateral deflections, closed circles lateral sets after the removal of the corresponding load. Wall 1A, concrete-block cavity wall; wall 2A, brick cavity wall; wall 3A, brick-tile.

joint in the back wythe at about two-thirds the height. The load at failure of the brick cavity walls loaded on one wythe only averaged 80 percent of the load at failure of the walls loaded on both wythes. Each of the brick-tile cavity-wall specimens failed by breaking of the tile in the upper two or three courses; no failure of the brick facing was observed.

5.2. Transverse Load

Transverse load tests were made with the wall in a vertical position. Two equal loads were applied, each along horizontal lines at one-quarter of the span from the supports toward the middle of the span. The wall rested against a roller near the top and another near the bottom, separated by a span of 7 ft 6 in.; the loading rollers were thus 3 ft 9 in. apart on the loaded wythe.

A wall under transverse load is shown in figure 8. The results of the transverse load tests are presented in table 5 and the lateral deflections in figure 9.

Each of the concrete-block cavity walls failed by rupture of the bond between the blocks and the mortar in both the face and the back wythes at bed joints, usually between the loading rollers. In the brick cavity walls, the bond failure occurred near a loading roller in both the loaded and opposite faces.

Three of the brick-tile cavity walls failed by rupture of the brick-mortar bond at midheight in the facing and by rupture of the bond between the

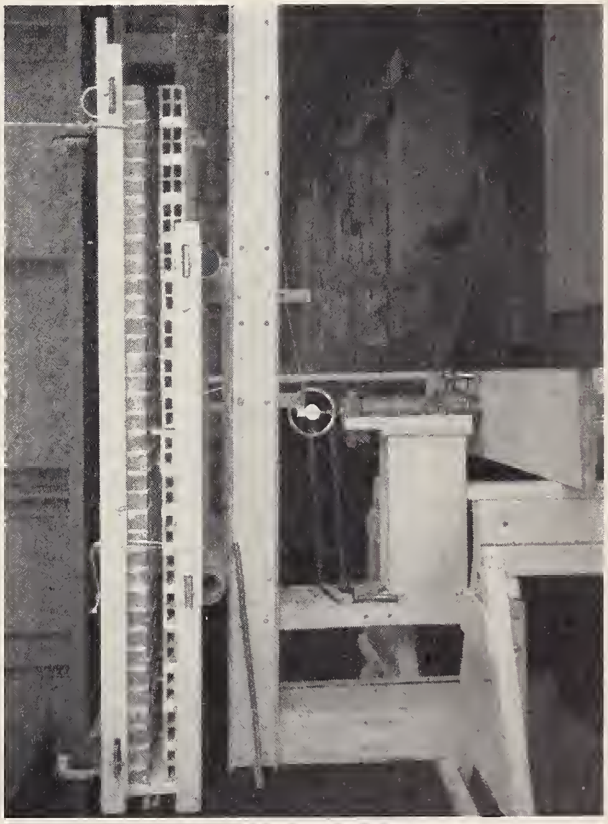

FIGURE 8. *Brick-tile cavity wall under transverse load.*

Loading rollers at quarter span are shown to the right of the wall.

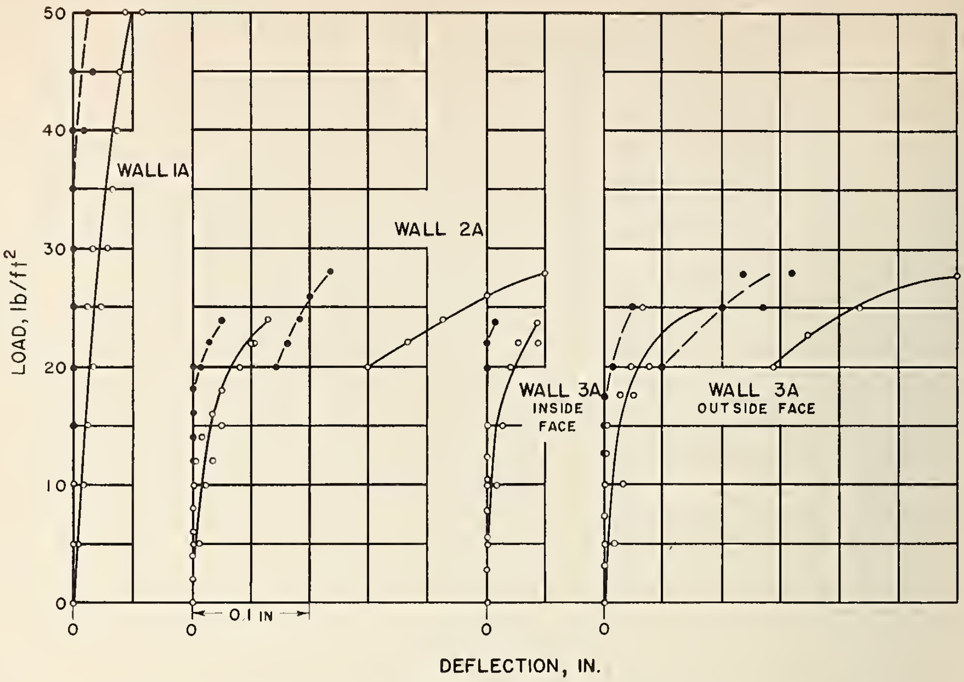

Figure 9. *Wall deflection under transverse load.*

Open circles represent deflections, closed circles sets after removal of the corresponding load. Wall 1A, concrete-block cavity wall; wall 2A, brick cavity wall; wall 3A, brick-tile cavity wall.

tile and the mortar at one or two bed joints at or between the loading rollers in the backing. For three other specimens, the bond between the tile and the mortar ruptured at a bed joint near mid-height in the backing, the bond rupture on the brick face occurring at a bed joint between the loading rollers in the facing.

5.3. Concentrated Load

A concentrated load was applied through a 1-in. diameter steel disc placed against the face of the test specimen at what was thought to be the weakest place. A wall under concentrated load is shown in figure 10.

Only one specimen failed below the 1,000-lb load obtainable with the apparatus used. This was one of the brick cavity walls on which the load had been applied at a head joint. Failure of this specimen occurred by rupture of the bond between the brick and mortar at a bed joint below when a 646-lb load was applied.

5.4. Impact Load

The impact loads were applied by allowing a 60-lb sand bag to swing as a pendulum. The bag struck the wall about the midpoint between four wall ties near the center of one face of the specimen. A wall preparatory to impact is shown in figure 11. The test results are given in table 5.

For the three concrete-block cavity walls, bed joints near midheight in both the face and back

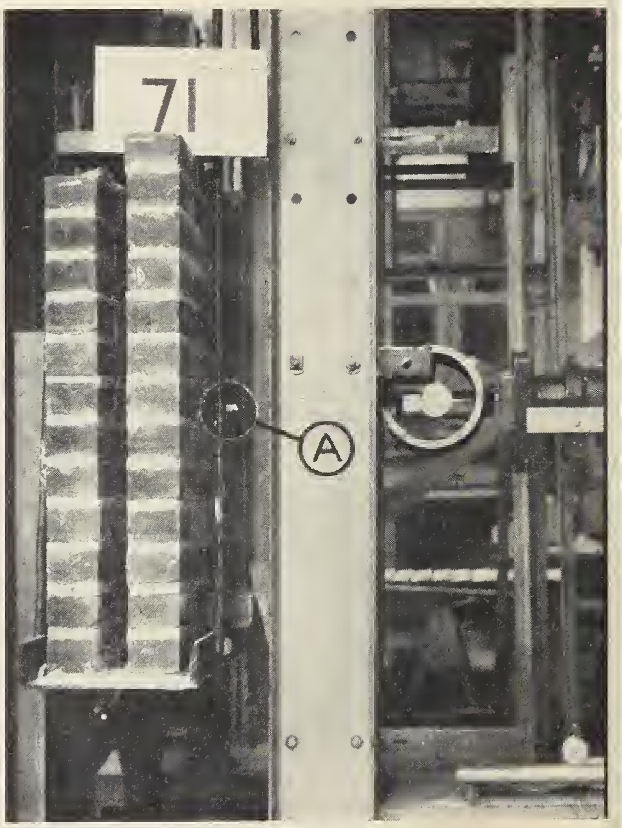

Figure 10. *Brick cavity wall under concentrated thrust.*

"A" indicates the point of application of load through 1-in. disk.

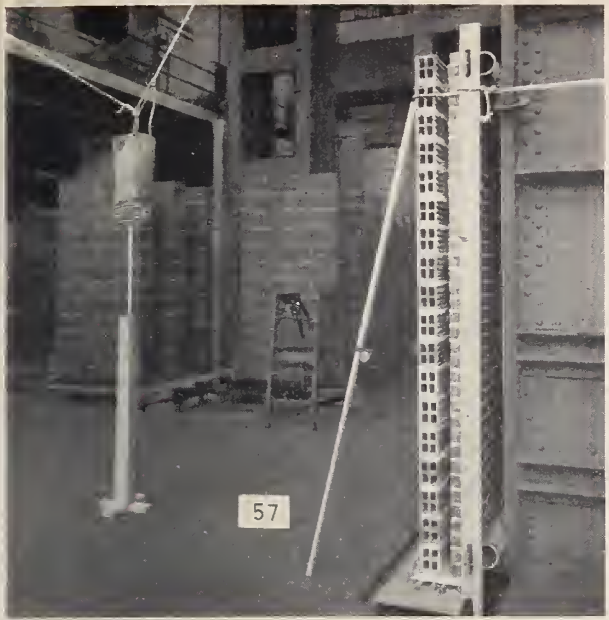

FIGURE 11. *Brick-tile cavity wall preparatory to impact test.*
Sandbag weighs 60 pounds.

wythes cracked at drops of 1.5, 2, and 2.5 ft, respectively. The tests were continued to failure, which finally occurred by displacement of the bond between the blocks and the mortar at those bed joints that had previously cracked.

For one of the brick cavity walls, a bed joint cracked near midheight at a drop of 1.5 ft, and another bed joint in the far wythe cracked at a 2.5-ft drop. A second specimen also showed a cracked bed joint at 1.5 ft. The tests were continued to failure, which finally occurred by rupture of the bond between the brick and the mortar at one or more joints on all three specimens.

For the three brick-tile cavity-wall specimens, the bond between the tile and the mortar in the back wythe ruptured transversely at or above midheight at drops of 1.5, 2, and 2 ft, respectively. The bond between the brick and the mortar in the facing ruptured transversely at or above the midspan at slightly higher drops. Both the backing and the facing finally failed by opening of these cracks or by the formation of new ones in the tile backing. For two of the specimens, both the back wythe and the face wythe failed at the same drop. For one of the specimens, the tile backing failed first, followed by failure of the brick facing at the next drop.

5.5. Racking Load

The test specimens were 8 by 8 ft, twice as large as any of the other walls for structural tests, and were braced on the lower corner to prevent horizontal sliding when thrust was applied. The loaded end was constrained from vertical movement by tie plates, but was allowed to move horizontally by a series of plates and rollers under the tie plates. The thrust was applied horizontally at the upper corner of the specimen and the

FIGURE 12. *Concrete-block cavity wall under racking load.*
Ties at top restrict vertical motion.
Compressometers measure horizontal deformation.

horizontal displacement relative to the fixed base measured at the other end of the wall (fig. 12). Test results are given in table 5.

The racking modulus given in table 5 is "the force causing a racking deformation of one foot for a wall one foot square, computed from the initial rate of deformation," reference [10]. Typical values of the racking modulus may be found in table 15 of reference [10].

One of the concrete-block walls failed by crushing of blocks in both the facing and the backing at the loaded corner. The other two failed by rupture of the blocks of both the face and back wythes approximately along a diagonal between the point of application of the load and the stop.

Two of the brick walls failed by rupture of both facing and backing along a diagonal between the point of application of load and the stop. The course of the cracks followed the joints in some places and passed directly through the brick in others. The third specimen failed by rupture of the back wythe only.

The tile wythe of each of the brick-tile walls failed by rupture between the masonry units and the mortar in the bed and head joints along a diagonal from the load to the stop. On only one of these walls did the brick facing fail.

6. Water Permeability

Because exterior masonry walls of houses or other buildings may be penetrated by wind-driven rains, with subsequent damage to the interior finish of such structures, the water permeability

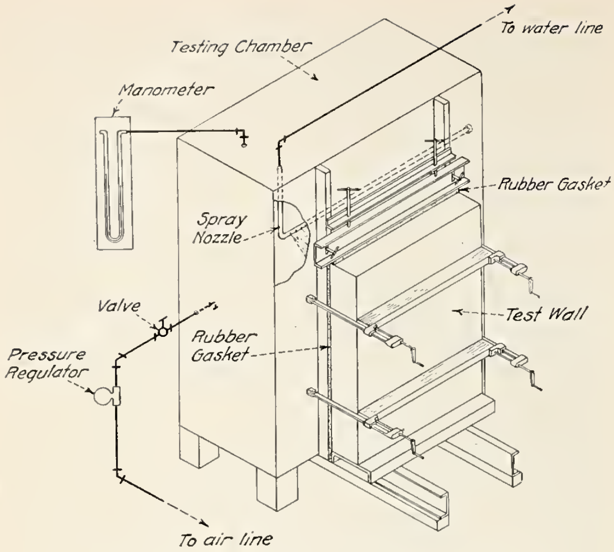

FIGURE 13. *Water-permeability test chamber.*

of one brick, three brick-tile, and one concrete-block cavity wall was examined and is reported in BMS82 [15].

6.1. Method of Testing

The test apparatus is shown in figure 13. The wall specimens were clamped into position against sponge-rubber gaskets so that the exposed face formed one side of a pressure chamber. Water from a perforated pipe was applied to the upper portion of the exposed face (inside the chamber), the 40-gal/hr rate being sufficient to cover the wall face with a thin sheet of flowing water. The applied air pressure maintained in the chamber was equal to that produced by a 2-in. head of water (approximately 10 lb/ft ^{2}), about the maximum pressure difference on two faces of a wall that might be caused by a 60-mph wind.

The air temperature in the testing room varied between 50° and 75° F. The walls were tested for not less than 1 day. As the backs of the walls had been painted with whitewash, the discoloration produced by moisture (dampness) on the back could be easily detected. The permeability test was more severe and of greater duration than the natural wind and rain storms to which most building walls are ordinarily subjected.

6.2. Test Results

With the exception of wall 1C, table 4, the backs of the walls remained dry during 1-day tests. Wall 1C became wet on the back above the flashing in 12 min.

The cavities in one of the brick-tile walls, 3C, was filled with 0.7 lb/ft^2 of shredded redwood bark; this wall was tested both before and after the cavity was filled. With the cavity open, some moisture appeared in the region around its reversed flashings in 10 hr, but in the retest, with the cavity filled, a large damp area appeared on the back in 0.2 hr. After the tests, when the backing wythes were removed, the shredded redwood bark remained standing; water was visible at only a few points on the back of the filling, but the inside of the brick wythe was dripping wet. The filling contained about 14 percent of moisture by weight before it was placed in the wall. After the tests, it contained 50 percent of moisture at the bottom and about 20 percent at the top of the wall.

According to the Armour Research Foundation and the Structural Clay Products Institute [16], a cavity wall filled with a specially designed pouring type of fiberglas, but having no wall ties, was tested and reported to have resisted moisture penetration through the back wythe for a period of several days. Apparently there was no differential air pressure across the cavity in these tests.

7. Heat Transfer

In order to determine the thermal insulating value of a cavity wall as compared to that of a solid wall, and to ascertain to what degree the ventilation of a cavity wall with outdoor air affects its insulating value, heat-transfer tests were made by H. E. Robinson of the Bureau's staff on brick, brick-tile, and concrete-block cavity walls. A solid brick wall was tested for comparison purposes.

7.1. Test Equipment and Procedure

In the guarded hot-box heat-transfer apparatus (fig. 14), heat flowed through the specimen from the electrically heated metering and guard boxes to the cold box, which was cooled by a refrigerating machine. The guard box was used so that the space surrounding the metering box could be maintained at substantially the same temperature as the interior of the metering box. This minimized heat exchange to or from the metering box except through the specimen. To keep heat exchange through the edges of the specimen to a minimum, the top and sides were encased by an insulated wooden enclosure (not shown in fig. 14).

For testing, the specimen was placed in the apparatus, the temperature in the cold box adjusted to approximately 0° F and that in the metering and guard boxes to 70° F. Air was circulated at approximately 35° F through the enclosure along the edges of the specimen. After a state of steady heat flow was attained, the heat transmittance of the specimen, indicated by the rate at which electric energy was supplied to the metering box, was observed.

In order to determine the effect of ventilation of the cavity on the heat-transfer properties of the brick and brick-tile cavity walls, six bricks were left out of the outside wythe, three at the third and three at the thirty-second courses, leaving openings into the cavity near both the bottom and the top of the wall. In one series of tests on the brick

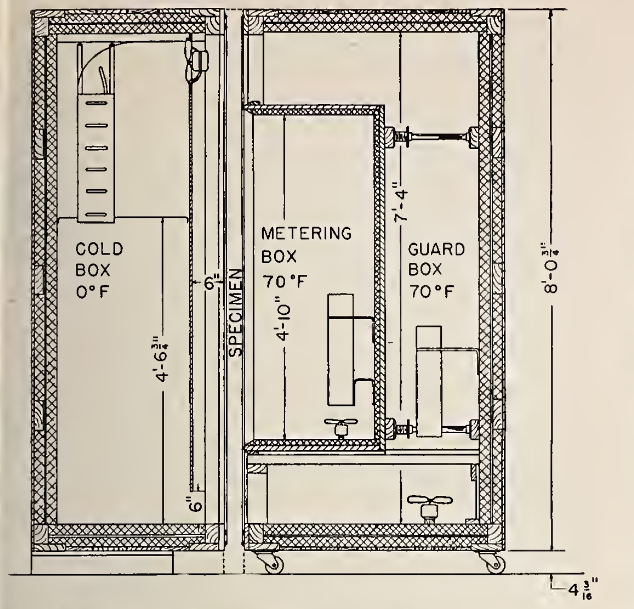

FIGURE 14. *Test apparatus for heat-transfer measurements.*

To minimize heat exchange through the edges, the top and sides of the specimen were encased in an insulated wooden enclosure not shown in this drawing.

wall 2D, the openings in the outside face were closed with brick chinked with sponge rubber, thereby completely sealing the cavity. In another series of tests (see table 6), the openings in the outside face were partly closed with brick and sponge rubber. Openings of 4.2-in.^{2} area, or 1.0 in.^{2} per linear foot of wall, were left at both top and bottom. In a further series of tests, the openings amounted to 7.2 in.^{2} in area, or 1.7 in.^{2} per linear foot of wall, and 89.0 in.^{2}, or 21.0 in.^{2} per linear foot, respectively.

Three series of tests were run on brick-tile cavity wall 3D, with the cavity completely sealed, with the openings between the bricks of 0.9 in.^{2} per linear horizontal foot at both the top and bottom, and with openings totaling 2.5 in.^{2} per linear foot at both top and bottom.

The cavity of the concrete-block wall, 1D, was not ventilated.

7.2. Test Results

The results of the tests on both ventilated and unventilated walls are given in table 6. In this table, the heat-transfer coefficients of the specimens are expressed in three ways. The observed thermal transmittance, u, is the number of Btu per hour transmitted through each square foot of the warm face of the specimen for each degree F difference in temperature of the air on the two sides of the wall, with air moving at a velocity of about 2 mph parallel to the faces on both sides of the wall. The coefficient u includes the effect of the warm-surface film coefficient f_i and the cold-surface film coefficient f_o, the values of which for the test conditions are presented in table 6. The film coefficients are expressed in Btu per hour per square foot of surface for each degree F difference in temperature between the surface and the air.

The thermal conductance, C, of each of the specimens is also presented, representing the number of Btu per hour transmitted through each square foot of the warm face of the specimen for each degree F difference in temperature of the two faces of the wall.

It is customary to express the heat-transfer coefficient of a building wall in terms of a selected thermal transmittance, U, corresponding to conditions of still air on the warm side and air moving at a velocity of 15 mph on the cold side of the wall. For these conditions, a value of 1.65 Btu/(hr)(ft^2)(°F) is taken for the warm-surface film coefficient, f_i, and 6.00 for the cold-surface film coefficient, f_o. Values of U, calculated from the test results, are presented in the table for each of the unventilated walls.

When walls 2D and 3D were tested with their cavities ventilated, the symbols u, U, C, and f_o were not applicable to the results as they are in ordinary cases because part of the heat was carried away by the ventilating air passing through the cavity. The quantity u as recorded in table 6 was in each of these cases, therefore, the observed heat flow through the area of the specimen covered by the metering box, in Btu per hour for each

TABLE 6. *Heat-transfer data*

	Concrete-block wall 1D (cavity unventilated)	Solid brick wall 2D–S	Brick wall 2D				Brick-tile wall 3D		
			Cavity unventilated	Cavity ventilated			Cavity unventilated	Cavity ventilated	
Openings for cavity ventilation at top and bottom of wall (in.^{2}/lin. ft of wall)	--------	------	0	1.0	1.7	21.0	0	0.90	2.5
Vertical distance between openings (ft)	--------	------	--------	7.2	7.2	7.2	--------	6.8	6.8
Observed thermal transmittance, u, Btu/(hr) (ft^2) (°F) [1]	0.25	0.44	.31	.33	.34	.45	.28	.28	.30
Corrected thermal transmittance, U Btu/(hr) (ft^2) (°F) [2]	.27	.53	.35	-----	-----	-----	.31	----	-----
Thermal conductance, C, Btu/(hr) (ft^2) (°F) [3]	.35	.89	.48	.51	.53	.69	.41	.42	.43
Warm surface film conductance, f_i, Btu/(hr) (ft^2) (°F)	1.97	1.85	1.95	1.96	1.89	1.94	2.04	2.07	2.04
Cold surface film conductance, f_o, Btu/(hr) (ft^2) (°F)	1.51	1.64	1.64	-----	-----	-----	1.46	----	-----
Estimated proportion of heat carried out by ventilating air (percent)	--------	------	--------	13	19	63	--------	7	17
Estimated rate of ventilating air flow through cavity, (ft^3/min)/lin. ft of wall	--------	------	--------	.4	.6	3.1	--------	.2	.6

[1] Between the air on the two sides of the wall, observed under test conditions.
[2] Between the air on the two sides of the wall, corrected for a 15-mph wind outside, and still air inside.
[3] Between the outer surface of the outer wythe and the inner surface of the inner wythe.

square foot and for each degree-F difference in temperature of the air on the two sides of the wall.

Solid counterparts of the brick-tile and the plastered concrete-block cavity walls were not tested, but it is estimated that their u values would have been about 0.38 and 0.34 Btu/(hr)(ft^2)(°F), respectively, and their U values about 0.44 and 0.38 Btu/(hr)(ft^2)(°F), respectively.

As would be expected, the measured u values of the unventilated cavity walls were considerably lower than those for their solid counterparts. The differences obtained in the u values of the solid and sealed-cavity counterparts were due to the insulating effect of the cavity air space, the average thermal conductance of which was approximately 1.0 Btu/(hr)(ft^2)(°F).

The u values of the ventilated cavity walls increased as the size of the ventilating openings was made larger. Estimated rates of ventilating air flow through the cavity and estimates of the percentage of the heat entering the cavity that was carried out by the ventilating air are presented in table 6. The u values of the brick and the brick-tile cavity walls were increased very little by the ventilation resulting from openings at top and bottom of approximately 1.0 in.^{2} per linear foot of wall.

8. Fire Resistance

Seven cavity walls were subjected to standard fire exposure according to American Standards Association Specification No. A2–1934 and the American Society for Testing Materials Specification E119–47, which require that a fire exposure with standard time-temperature relation[3] shall be applied to the wall. The specifications require that the wall must carry a continuously applied load sufficient to cause the maximum allowable working stress. The first of the following criteria to occur defines failure: (1) An average temperature rise of 250 deg F or a maximum rise of 325 deg F measured with thermocouples under asbestos pads on the unexposed side of the wall, (2) the passage of heat, gases, or flame through the specimen intense enough to ignite cotton waste, or (3) structural failure.

The walls were contained within frames that were moved into place to form one side of the furnace chamber. They were restrained within the panel frame with a constant compressive load applied vertically. One wall was tested fully restrained. None of the cavities was ventilated.

[3] The standard furnace temperatures are: 1,000° F at 5 min; 1,300° F at 10 min; 1,550° F at 30 min; 1,700° F at 1 hr; 1,850° F at 2 hr; 2,000° F at 4 hr; 2,300° F at 8 hr.

8.1. Test Specimens

Two of the seven walls tested were of concrete block, three of brick, and two of structural clay tile. Construction details are given in table 4, curing and loading details in table 7. A concrete block cavity wall in position for test is shown in figure 15.

In general, a plate covering both wythes served to distribute the loads, which were applied uniformly along a line parallel to the faces of the walls. Walls 1E-1 and 1E-2 of hollow masonry units were loaded centrally, 1E-1 to 80 lb/in.^{2} of gross area, corresponding to 100 lb/in.^{2} of gross less cavity area, and 1E-2 to 80 lb/in.^{2} of gross less cavity area. The mortar of wall 1E-1 as tested in cubes averaged 1,403 lb/in.^{2}, that of wall 1E-2, 2,560 lb/in.^{2} (both 1:1:6 by volume). These walls were described in BMS117 [17] and BMS120 [18]. The brick walls were laid in winter, and the brick were dampened only slightly. As disclosed by examination after the tests, the mortar bond was considered good.

Wall 2E-1 was loaded centrally to 236,250 lb, or 125 lb/in.^{2}, of gross area, corresponding to 156 lb/in.^{2} of gross area less cavity area. The load on wall 2E-2 was 72,000 lb, applied 1⅝ in. off center toward the side exposed to the fire, corresponding to an average load of 80 lb/in.^{2} on the exposed wythe and 28 lb/in.^{2} on the unexposed wythe. This load is representative of the actual load that

TABLE 7. *Summary of fire-test data*

Workmanship commercial, that is, head or cross joints not solidly filled

Wall	Material	Mortar (by volume)	Curing	Loading			Fire intensity	Failure		Maximum deflection
				Exposed wythe	Unexposed wythe	Eccentricity		Type	Time	
			Days	*lb/in.²*	*lb/in.²*	*in.*	*Percent*		*hr min*	*in.*
1E-1	Concrete block [1]	1:1:6 (B)	32	100	100	0	101.2	Load	1 16	3.4
1E-2	do [1]	1:1:6 (B)	30	80	80	0	100	Avg temp rise	[2] 3 45	1.1
									[2] 4 43	2.4
2E-1	Brick	1:1:6 (B)	48	156	156	0	101	Load	1 16	3.4
2E-2	do	1:1:6 (B)	33	80	28	1⅝	100	Avg temp rise	5 15	3.4
2E-3	do	1:1:6 (B)	41	(3)	(3)	(3)	100	do	4 55	4.2
4A-1	Hollow tile [4]	1:1:4	34	125	25	2	96	do	4 7	1.1
4A-2	do [4]	1:1:4	34	125	25	2	98	do	4 6	1.2

[1] The concrete-block walls were each divided into two separate 8- by 11-ft sections. Wall 1E-1 had one section of cinder aggregate and one section of sand-and-gravel aggregate.
[2] First line refers to section of wall with cinder aggregate; second line to section of wall with foamed-slag aggregate.
[3] Restrained from expansion in the plane of the frame.
[4] Fire clay and gypsum plaster on exposed side; 1:3 cement plus 15 percent of lime on unexposed side. 4A-1 end construction; 4A-2 side construction.

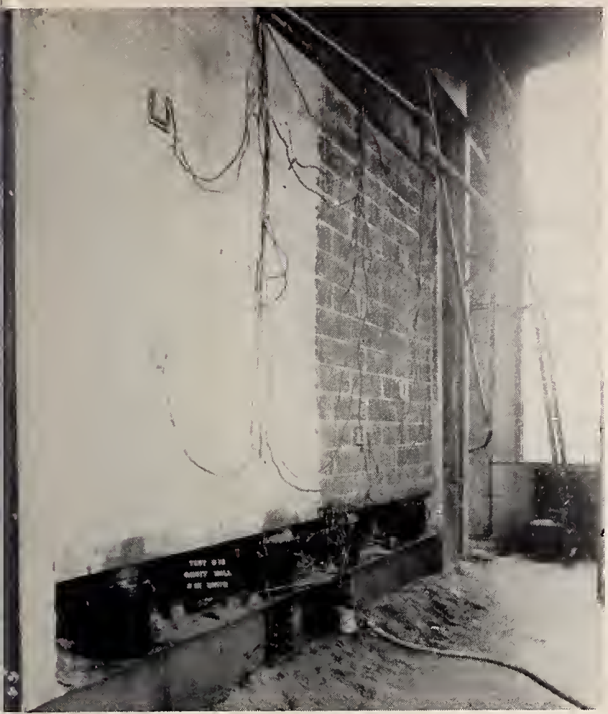

Figure 15. *Concrete-masonry cavity wall in position for fire test.*

One 8- by 11-ft section consisted of cinder-concrete units, the other of sand and gravel-concrete units

would be applied to an exterior wall under the limitations of some building codes.

Wall 2E-3 was tested restrained within panel frames made of 20-in. 120-lb girder beams under conditions representative of installation within the framework of fire-resistive buidlings.

Gypsum plaster was applied to the exposed sides of the structural clay-tile walls, 4A-1 and 4A-2, 1:3 cement plus 15 percent of lime on the unexposed side. The load on these walls was applied 2 in. from the center toward the exposed face and resulted in an average load of 125 lb/in.^{2} on the exposed wythes and 25 lb/in.^{2} on the unexposed wythes. These walls are described in "Fire Resistance of Hollow Load-Bearing Walls" [19].

8.2 Test Results

The time and type of failure of the walls and maximum deflection at failure are listed in table 7. Figure 16 gives time-temperature curves for one of the brick walls, 2E-2. Two of the walls collapsed under load after approximately 1¼ hr of fire exposure; all the others withstood the fire and failed by the temperature-rise criterion at times of 3¾ hr or more. The temperatures on the exposed faces of all the walls were similar at corresponding phases of the tests. The walls which failed structurally, 1E-1 and 2E-1, showed much larger deflections than the others; for in-

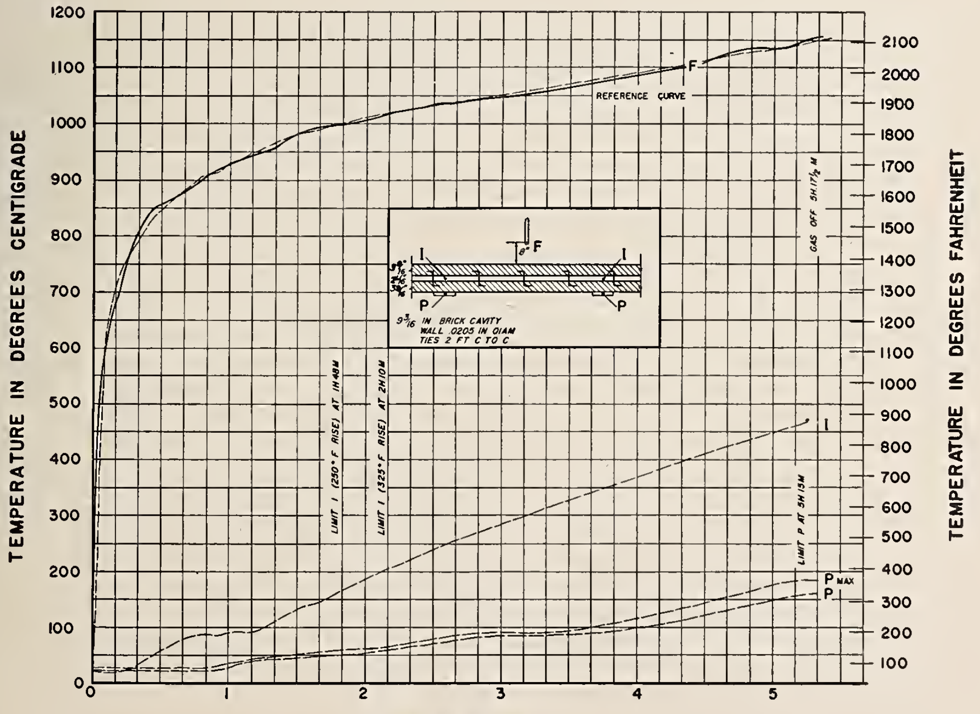

Figure 16. *Time-temperature curves for a brick cavity wall*

F, Furnace temperatures; I, temperatures in the cavity; P, unexposed-surface temperatures.

stance, the maximum deflection of wall 1E-1 at 1 hr 10 min was 3.4 in. compared to a maximum deflection of wall 1E-2 at 4 hr 40 min of only 2.4 min.

Wall 1E-1 was loaded centrally to 100 lb/in.^{2} of gross area less cavity area; the maximum allowable compressive load for this type of construction loaded centrally is given in reference [4], subsequently developed, as 63 lb/in.^{2}, and in the tentative revision (table 1, footnote) as 69 lb/in.^{2}. Wall 1E-1 also used a weaker mortar than wall 1E-2.

Wall 2E-1 was loaded centrally to 156 lb/in.^{2} of gross area less cavity area; the maximum allowable compressive load for this type of construction loaded centrally is given in reference [4] as 125 lb/in.^{2} and in the tentative revision (table 1, footnote) as 100 lb/in.^{2}.

The distance from the center point of the wall at midheight and the line of application of load becomes smaller as bowing takes place during fire exposure only when the load is applied eccentrically toward the exposed (back) wythe; this type of loading thus tends to be more stable than central, or uniformly distributed, loading. For example, for a centrally loaded wall and a 3-in. bow, the line of loading would be about 2 in. from the outside face of the outer wythe at the midheight of the wall. Because the most severe exposure is on the inside of a structure, and as cavity walls are used predominantly as exterior walls, eccentric loading toward the exposed face is not only favorable to a longer fire endurance but also represents the usual application.

In none of the tests did the temperature in the cavity become high enough to cause failure of the metal ties. Although these cavity walls were tested unventilated, experience with fire-endurance tests of walls with large cracks indicates that the fire endurance would not be materially affected by weep holes.

As supplemental information, the fire resistance for some unventilated cavity walls with and without plaster and with and without combustible members framed into the wall are presented in table 8.

Table 8 is adapted from National Bureau of Standards Building Materials and Structures Report BMS92 [20]. The fire-resistance ratings apply where the mortar mixes are not leaner than 1:1:6 for brick and concrete blocks, and not leaner than 1:1:4 for structural clay tile. Loads are assumed to be applied eccentrically. Ratings were generally rounded off to a period just shorter than the test results; some of the ratings were obtained by S. H. Ingberg by interpolating or extrapolating actual test data. The effects of plaster were derived from test results and accepted formulas. The thicknesses for which endurance ratings are given are those most likely to be found in building construction. Ratings for plastered brick and concrete-block walls are for ½-in. plaster thickness and for structural clay tile are for ⅝-in. thickness inside and ¾-in. portland-cement stucco outside.

9. Discussion and Summary

No failure of the ties was observed in the structural tests listed in table 4. However, tests on wall-tie assemblies, described in BMS101 [6], indicated the importance of the mortar in determining the type of the failure and under what conditions it would occur. Thus, for 1,000-lb/in.^{2} mortar, a typical assembly tested in compression failed by buckling of the ties; for 270-lb/in.^{2} mortar, specimens failed by crushing of the mortar against the ends of the ties.

Assuming a tie spacing of one per 4½ ft^2 of wall area, any of the 6-, 8-, or 10-gage steel or copperweld Z-shaped or rectangular ties provided adequate bonding between the two wythes to maintain the relative positions of the wythes against the usual lateral loads to which such walls may be subjected. Ties in cavity walls are intended to connect the two tiers and to serve as

Table 8. *Estimated fire resistance of cavity walls*

Interpolated results taken from BMS92. All the walls have 2-in. wide cavities; all are loading-bearing. Where plaster is indicated, it is assumed to be not less than ½-in. of 1:3 sanded gypsum plaster. For the tile, ¾ in. of plaster or stucco outside and ⅝ in. of plaster inside were applied

Nominal wall thickness	Description	Proportion of cored spaces in units	Fire-resistance period: Incombustible members framed into wall or no framed-in members			Fire-resistance period: Combustible members framed into wall	
			No plaster	Plaster on one side [2]	Plaster on two sides	No plaster	Plaster on exposed side
in.		*Percent*	*hr*	*hr*	*hr*	*hr*	*hr*
9	Clay or shale brick	0	5	6	7	2	2½
10	Structural clay or shale tile (3¾-in. tile)	60	-------	-------	4	-------	-------
10	Cored concrete-masonry units (expanded slag or pumice aggregates)	38	4	5	6	1½	2
10	Cored concrete-masonry units (expanded burned clay or shale, crushed limestone, air-cooled slag, or cinders)	38	3½	4	5	1¼	2
10	Cored concrete-masonry units [1] (calcareous sand and gravel)	38	-------	-------	5	1¼	1¾

[1] Coarse aggregate, 60 percent or more calcite and dolomite. [2] No plaster on fire-exposed side.

struts or tension members between them. Wall ties of the types tested did not have sufficient flexural rigidity to transmit shearing forces across the cavity. Consequently, when one wythe was subjected to a vertical load, only a small part of the load was transmitted to the other, and the two tiers did not exert common action under such loading.

Exact comparison between the structural tests on cavity walls and similar tests on solid walls or walls with continuous masonry bridges [8, 21] was not possible because of the difficulty of adequately reproducing mortar and workmanship and, for some of the tests, conditions of curing. For most of the compressive-strength tests, too, the distribution of the load over both wythes was not completely typical of conditions to be met in service. Rough generalizations that could be made by comparing these test results, however, lead to the conclusion that for compressive loads with both wythes loaded, for concentrated loads, for racking loads, and for impact loads, the performance of the cavity walls was approximately equivalent to that of walls without cavities, using the same type and quantity of material; for transverse loads the performance was inferior to that of conventional walls for similar materials and workmanship. The tests indicated that cavity walls built according to accepted specifications [4] and having adequate workmanship will withstand reasonable impact and the usual floor and roof loadings of a two-story dwelling.

Results of tests indicate that while the outer wythe may be highly permeable to wind-driven rain, the proper inclusion of flashing and weep holes gives adequate protection against leakage through the inner wythe. When highly permeable concrete-masonry units were used in the facing wythe, it was necessary to apply a protective coating, consisting of portland-cement paint, to the exterior surface.

The thermal-insulating properties of a cavity wall depended upon the construction, air permeability, ventilation allowed, etc. In general, an improvement of over 25 percent in insulating properties was found for unventilated cavity walls compared with solid walls of the same material. A small amount of ventilation, not exceeding 1 in.^{2} of opening at the top and bottom per linear foot of wall, did not materially increase the thermal transmittance of the walls.

The fire resistance of unventilated cavity walls was not much different from that of walls having the same quantity of solid materials except for the load-bearing ability. In the fire tests of those walls on which the loads applied were within the limits given in "Tile Engineering" [3] and table 1 of this report, structural failure was not observed before failure by rise of temperature on the unexposed face. The condition of loading favorable to structural stability during fire occurred when the load was applied eccentrically toward the exposed (inner) wythe, a condition that would occur in most applications.

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BUILDING MATERIALS AND STRUCTURES REPORTS

[Continued from cover page II]

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[List continued on cover page IV]

BUILDING MATERIALS AND STRUCTURES REPORTS

[Continued from cover page III]

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