Water Permeability of Structural Clay Tile Facing Walls

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ACKNOWLEDGMENTS

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Bethlehem Brick Company, Bethlehem, Pennsylvania
Charleston Clay Products Company, Charleston, West Virginia
Cherokee Brick Company, Macon, Georgia
Elgin Butler Company, Butler, Texas
Kalo Tile Company, Fort Dodge, Iowa
Mason City Brick and Tile Company, Mason City, Iowa
Midland Tile and Brick Company, Chillicothe, Missouri
Reliance Clay Products Company, Mineral Wells, Texas
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This research work was directed by Joseph A. Wise, Professor of Civil Engineering. Mr. Sylvio P. Bunea and Mr. Eugene E. Covert, Research Assistants in the Department of Civil Engineering, were in charge of the laboratory work during different phases of the project.

Water Permeability of Structural Clay Tile Facing Walls

INTRODUCTION

Structural clay tile has been used for exterior facing walls of buildings with varying success in the past. Water and rain driven by strong wind have often penetrated through such walls. Structural clay tile is a highly durable material, and, if water-tightness could be assured, it is well suited for exterior wall construction. It possesses high strength and has a comparatively low coefficient of thermal conductivity. Some of the tile currently being marketed are well suited for exterior walls from the standpoint of architectural appearance. Such walls can usually be constructed at much less cost than a wall with face brick and either common brick or tile backing. Supplies of clay are quite plentiful and extensive in distribution, and tile can be produced in large quantities with present plants and equipment. If water-tightness could be secured, such walls would be more extensively used, with resultant lowering of construction costs.

Previous research by others had indicated that walls constructed using mortar of certain good characteristics and using good workmanship had suffered less from permeation of water than those in which poor workmanship or mortar had been employed *(29, 46, 47, 48)*.[1] Other factors, such as outdoor exposure, wetting and drying, heating and cooling, etc., did not appear to have any very significant effect. In one report, *(47)* it was noted that end construction panels appeared to be slightly less permeable than side construction panels.

The primary purpose of this research was to investigate the relative efficiencies of various types of construction with respect to water permeability. In addition, certain integral waterproofing compounds were used in the mortar of some panels. Other tests included the effect of curing panels 28 days in a moist room, the use of very dry and very wet mortars, the use of stiffened and retempered mortar, the laying of walls in freezing weather, and the use of a vertical open head space in the head joints of a side construction panel. The ultimate objective was to ascertain the essential factors relating to water permeability of such walls.

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[1] The italic figures in parentheses refer to the Bibliography, pp. 29-32.

Table I. Types of Tile Construction

Type	Solid Shell				Double Shell				Cored Shell			
	Bed		End		Bed		End		Bed		End	
	Flat	Divided	Plain	Recessed	Flat	Divided	Plain	Recessed	Flat	Divided	Plain	Recessed
FTX												
1. Standard												
a. Side	a											
b. End			h					m				
2. Heavy Duty												
a. Side												
b. End			v				R	e, E*				
FTS												
1. Standard												
a. Side	B	c				g						
b. End												
2. Heavy Duty												
a. Side					d	A				b		
b. End			p									t

* E is similar to e, but it has a 6-inch wall thickness.

TEST PROGRAM

Types of Test Panels

For the investigation of the effect of type of construction, 14 different types of eight-inch tile were used, and, in addition, one type was duplicated in a six-inch wall. The types used, as shown in Table I, and the classifications, conform to those of the American Society for Testing Materials, ASTM Designation C 34-41 *(53)*. In addition, isometric scale drawings of each type are shown in Figures 1 to 15.

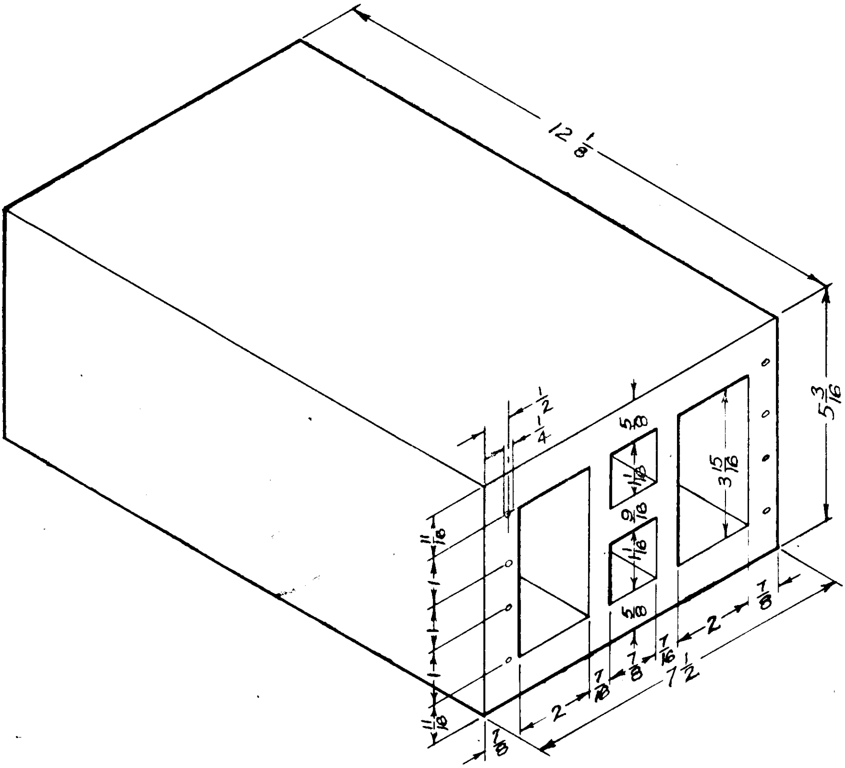


Figure 1. Construction of Tile α

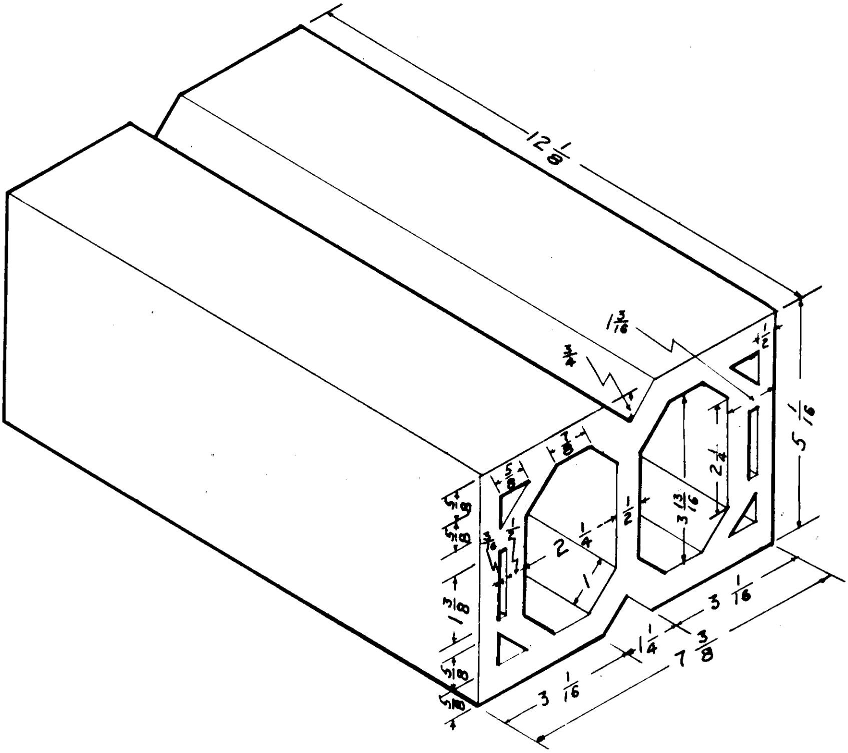


Figure 2. Construction of Tile A

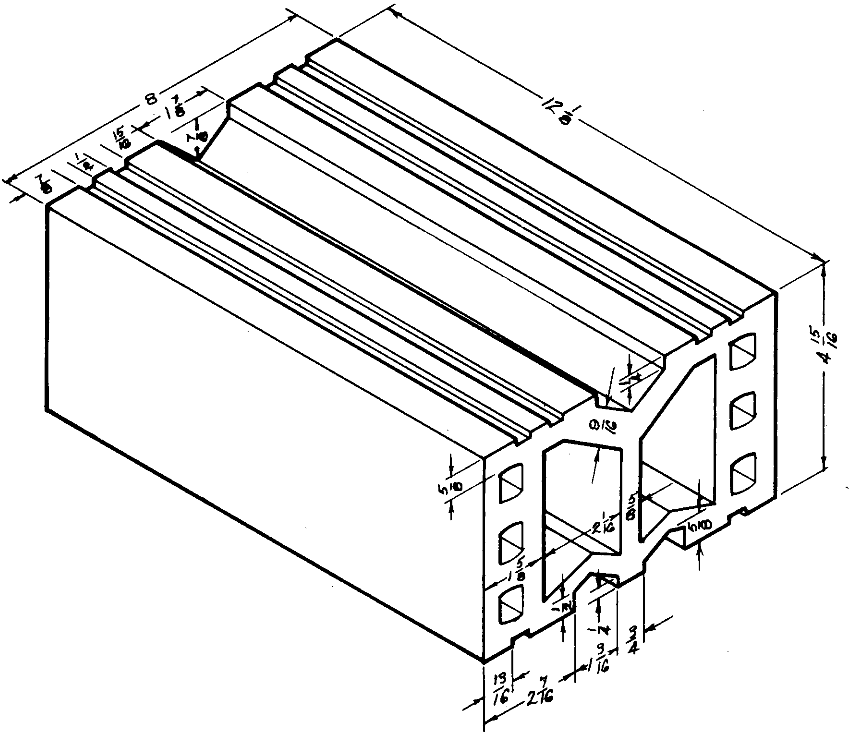


Figure 3. Construction of Tile b

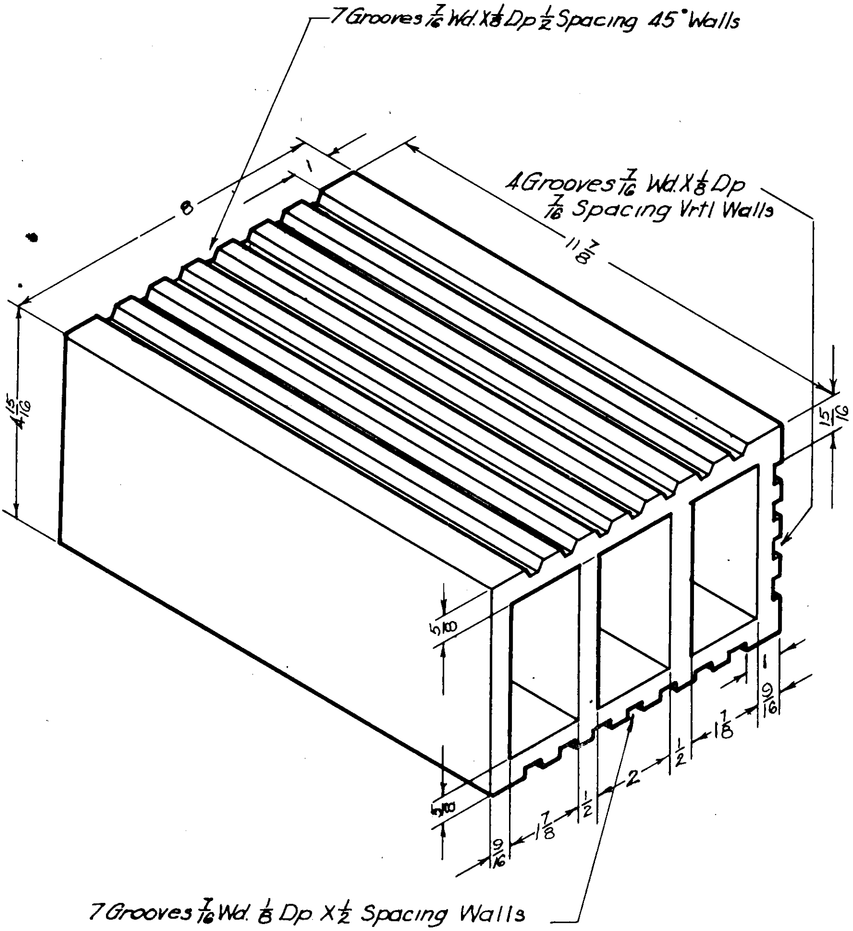


Figure 4. Construction of Tile B

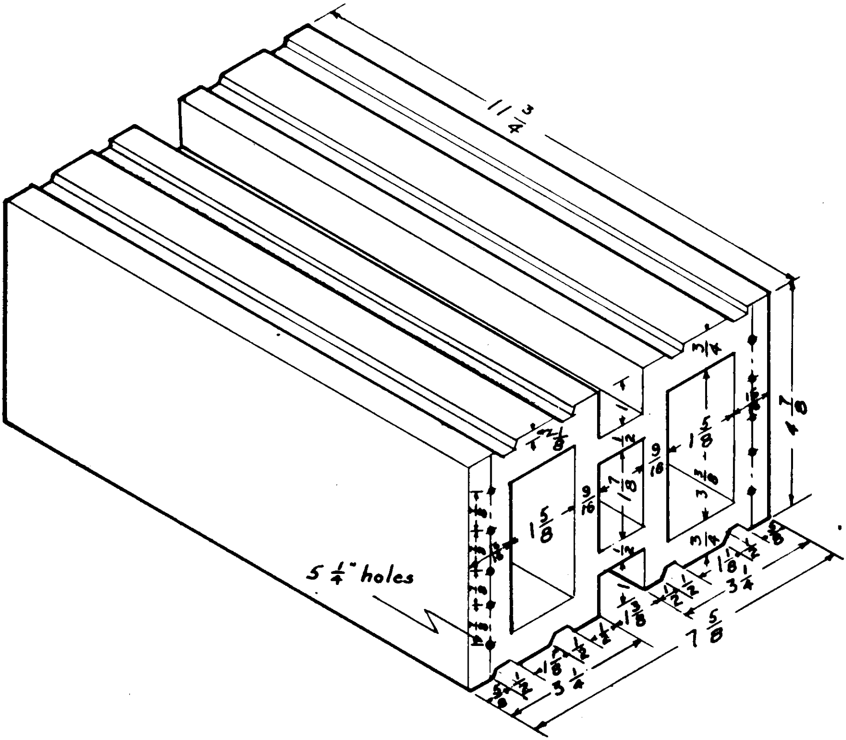


Figure 5. Construction of Tile c

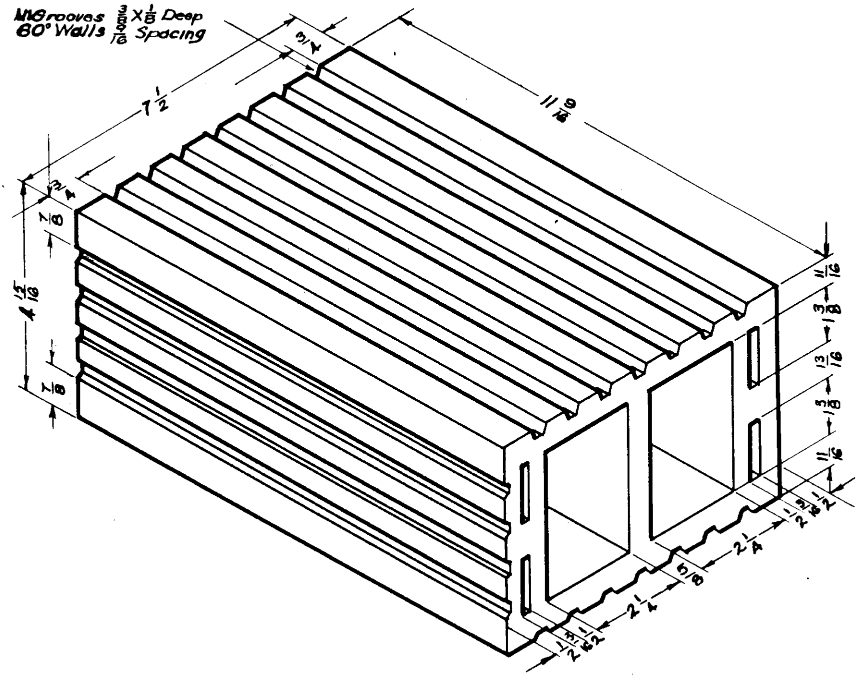


Figure 6. Construction of Tile d

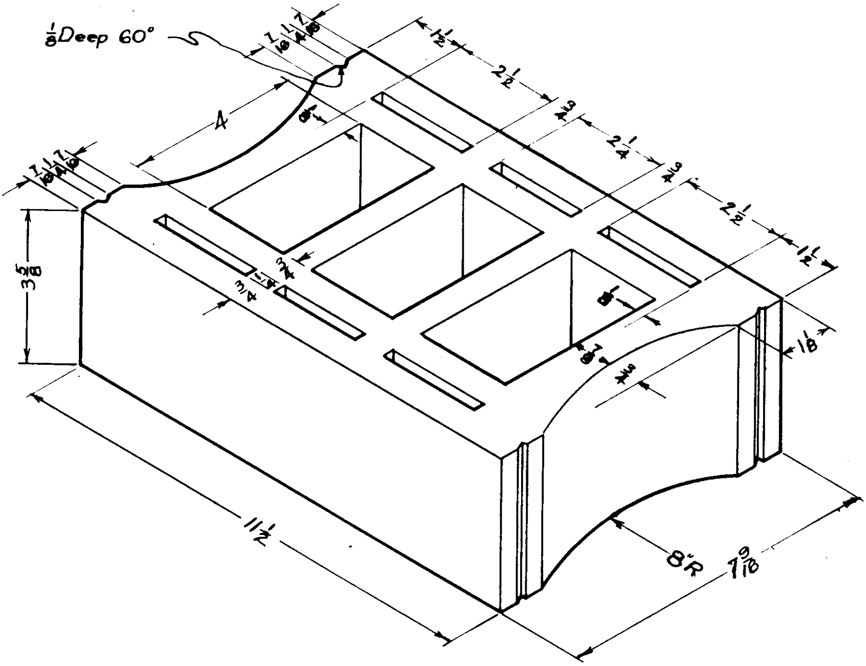


Figure 7. Construction of Tile e

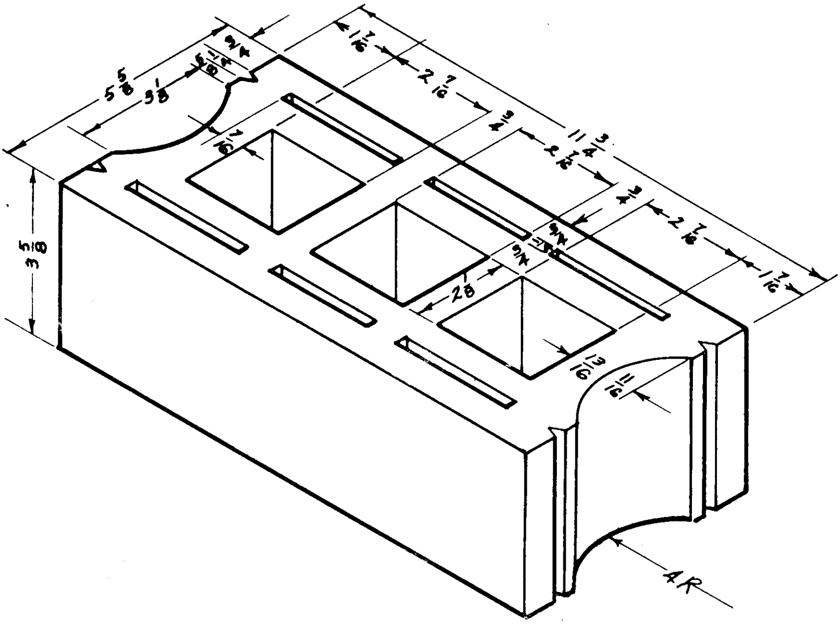


Figure 8. Construction of Tile E

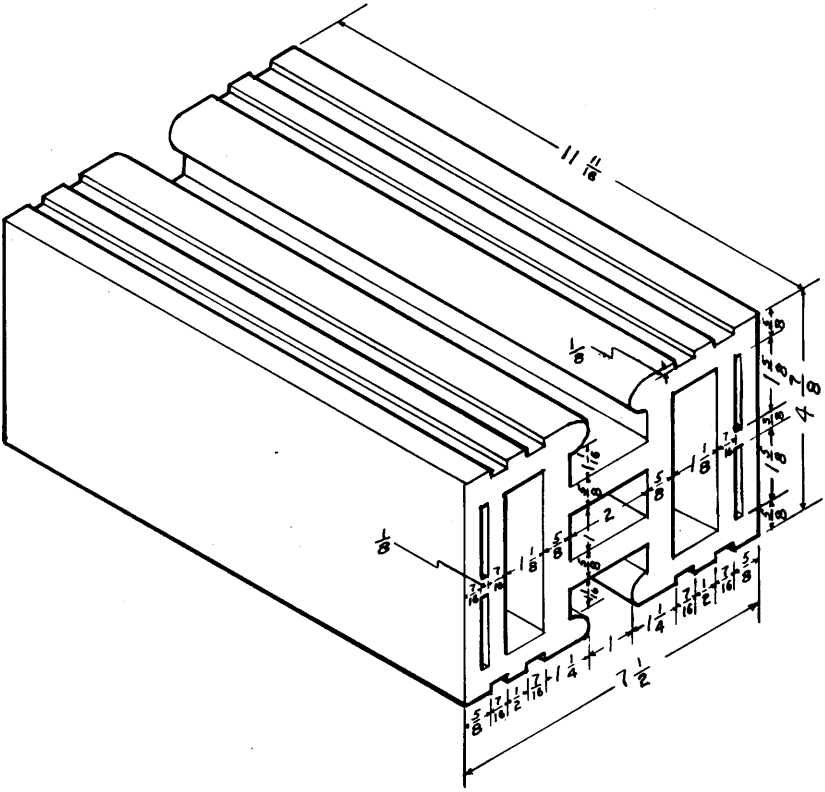


Figure 9. Construction of Tile g

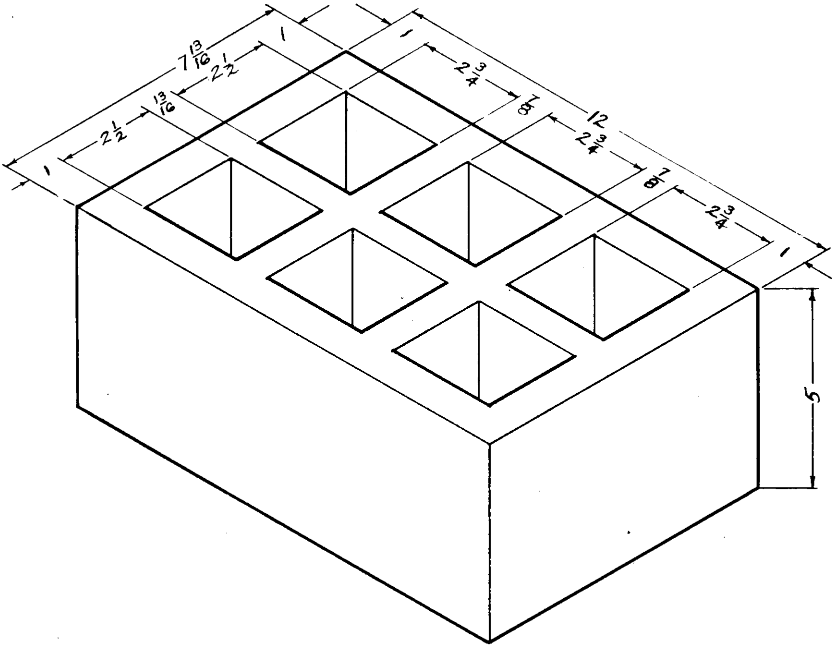


Figure 10. Construction of Tile h

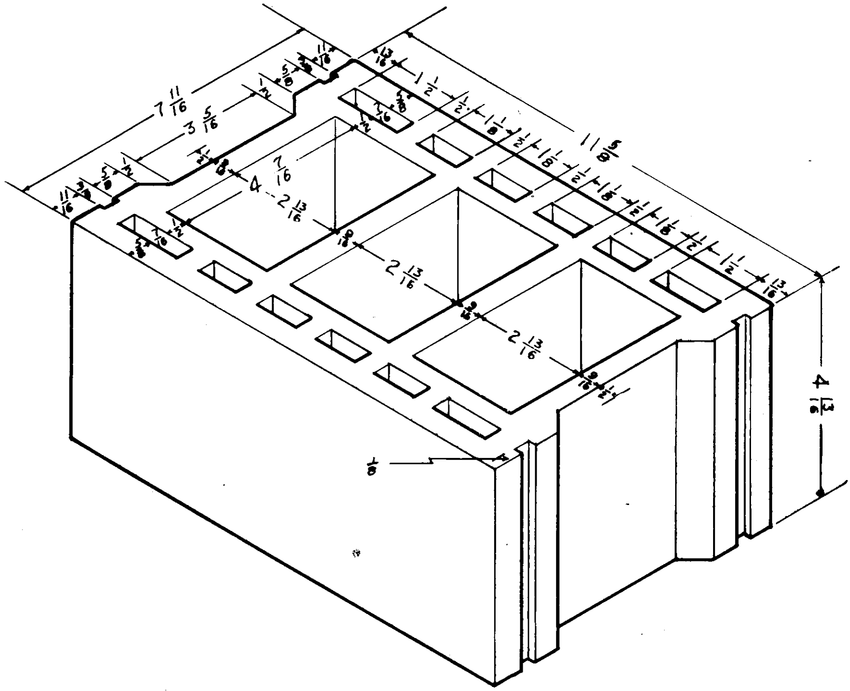


Figure 11. Construction of Tile m

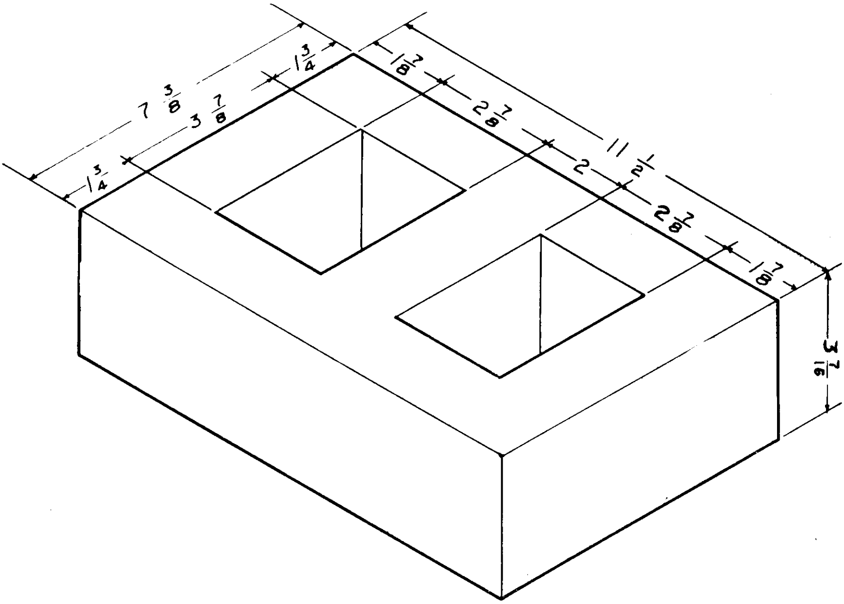


Figure 12. Construction of Tile p

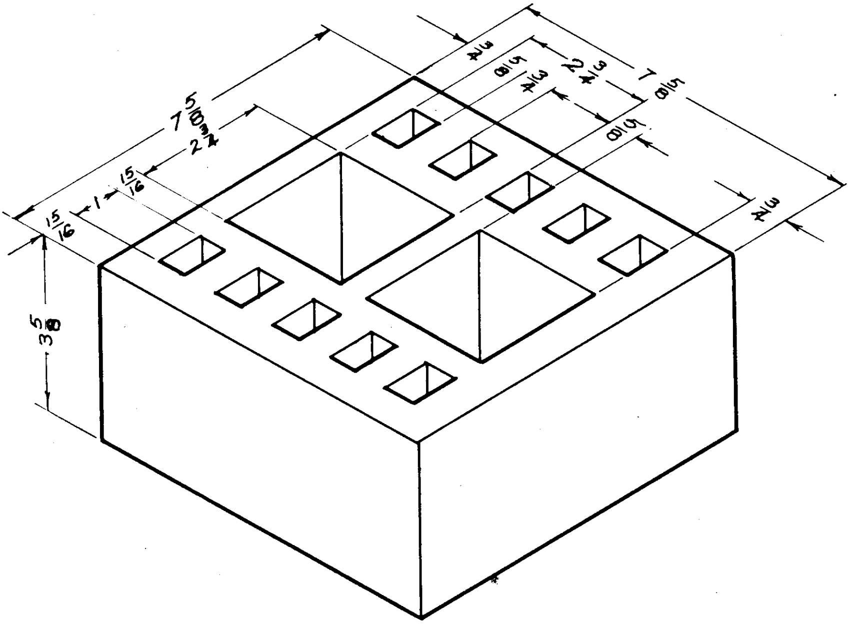


Figure 13. Construction of Tile R

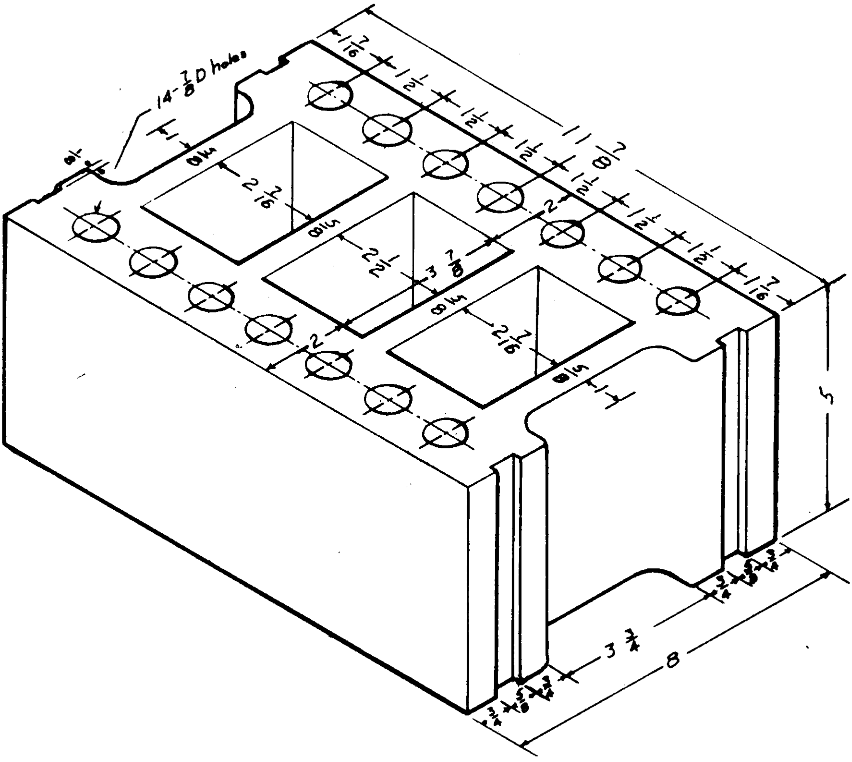


Figure 14. Construction of Tile t

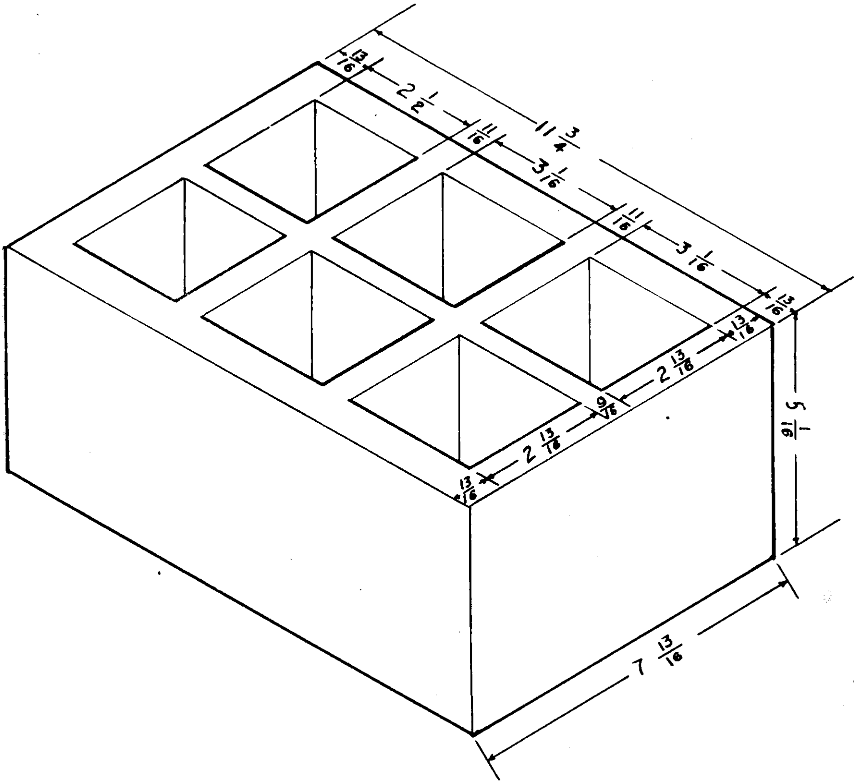


Figure 15. Construction of Tile v

The additional test panels are indicated in the following list:

1. Integral Waterproofing Compounds Added to Mortar
   Brickron, Master Builders, waterproofing
   Hydratite, A. C. Horn, waterproofing
   Mortite, Truscon Company, waterproofing
   Vinsol resin
   Mortar mix (ground clay to replace lime)
2. Mortar Variations
   Retempered mortar
   Partially set mortar
   Very wet mortar
   Very dry mortar
3. Curing and Exposure
   Curing 28 days in a moist room
   Built outdoors and left 28 days in freezing weather
4. Joint Variation
   Vertical open space in head joints.

All panels were given a 24-hour permeability test, then dried to constant weight and given a five-day permeability test. After

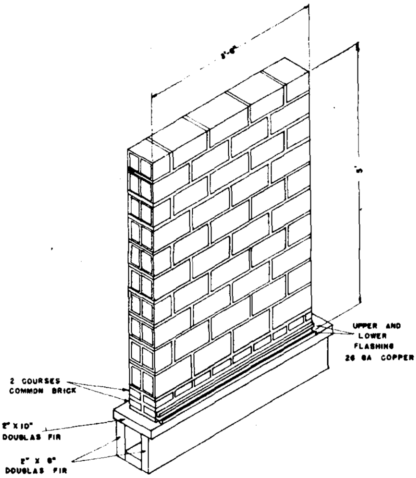


Figure 16. Construction of Typical Panel

Figure 17. Typical Test Panel

these tests were completed, most of the test panels were taken apart, and the joints were examined to determine the path taken by the water passing through them.

Construction of Test Panels

Because the tile were received from different plants, each type was given an identification letter. Wood bases were prepared for all panels, and roofing nails were driven into the top of the wood base to provide bond to mortar. Two courses of brick were then placed on the wood base. Two copper flashings were built into the brick base, and weep holes were left in the head joints of the brick so that they drained into the flashings. The tile panel was then built up on this brick base. General dimensions and details are shown in Figure 16. Figure 17 shows a typical panel. An experienced brick mason was employed to lay the brick and the tile. All exterior joints were tooled with a round nose tool, and interior joints were struck flush. The bed joints were filled (except for tile with divided bed) and the head joints were full buttered and shoved into place. Recessed ends were buttered at interior and exterior edges only. The mortar was composed of one part Portland cement, one part lime and 5.2 parts sand, by volume. All ingredients, including water, were weighed for each batch. Moisture in the sand was determined, and water added was corrected for this moisture. The sand was selected, from several samples collected locally, as the one most nearly conforming to the requirements of the American Standard Building Code Requirements for Masonry of the National Bureau of Standards, M 174 *(56)*. (Fig. 18.)

Flow tests were made of all mortar batches. The flow table used at the University of Minnesota was subsequently calibrated by using a mixture supplied by the Cement Reference Laboratory of the National Bureau of Standards. It was found that this

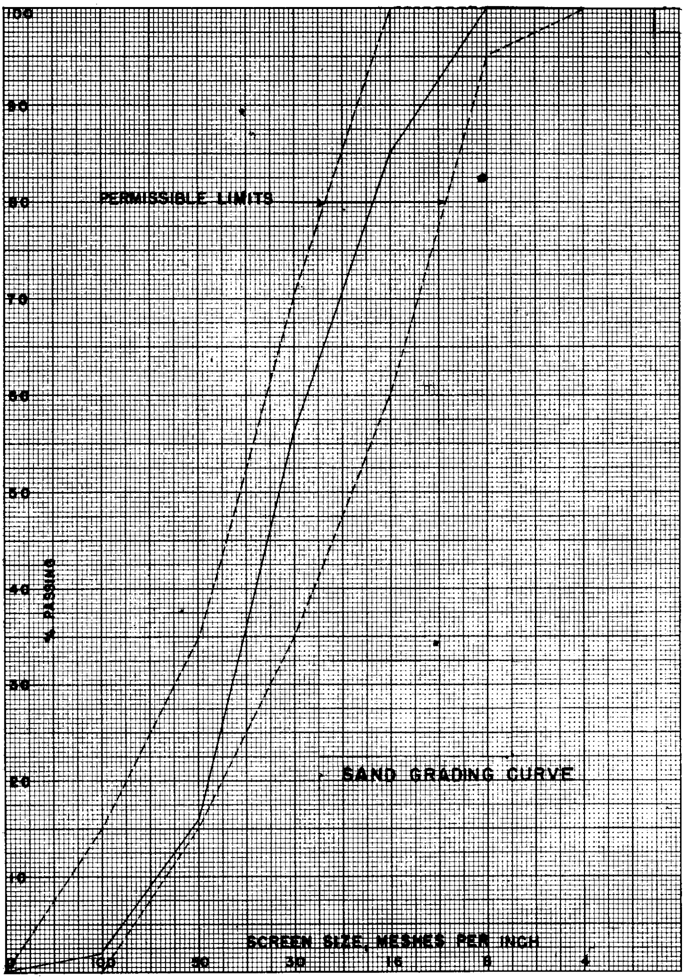
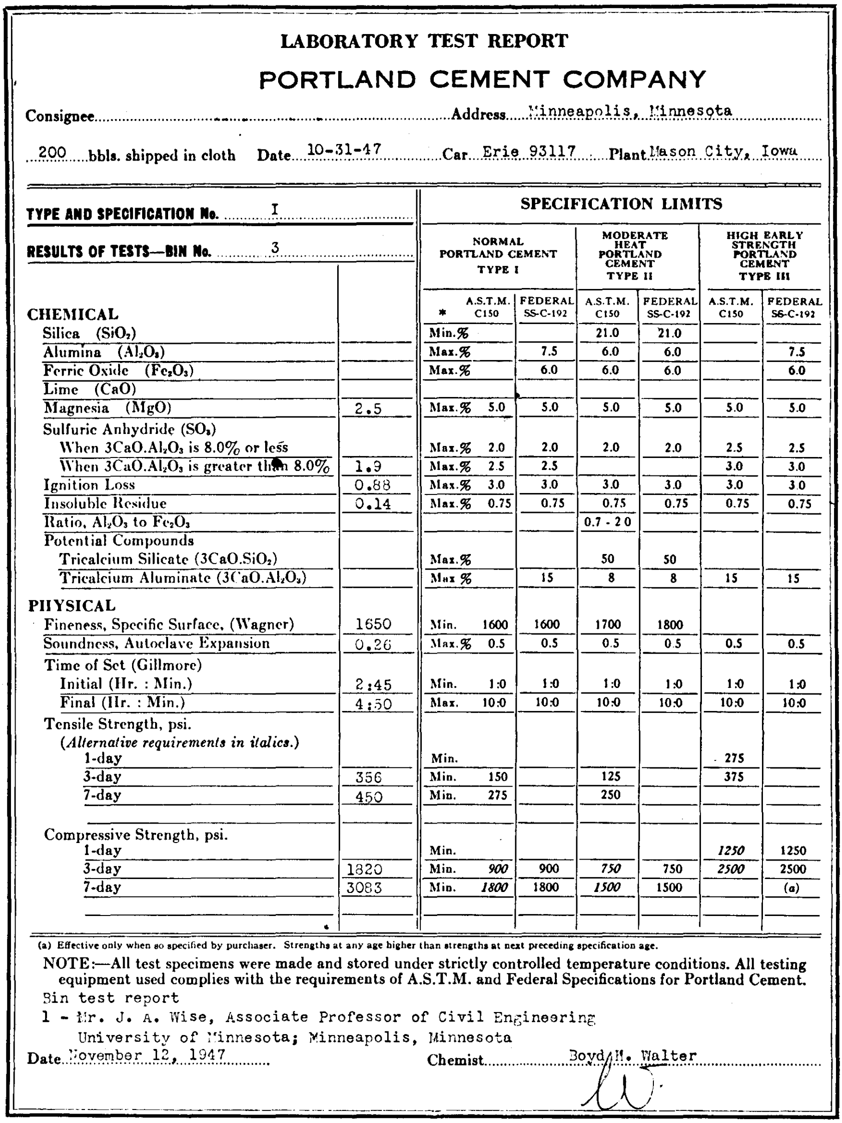


Figure 18. Sand Grading Curve



LABORATORY TEST REPORT

PORTLAND CEMENT COMPANY

Consignee.......................................Address Minneapolis, Minnesota

200 bbls. shipped in cloth Date 10-31-47 Car Erie 93117 Plant Mason City, Iowa

TYPE AND SPECIFICATION No. I

RESULTS OF TESTS—BIN No. 3

		SPECIFICATION LIMITS						
		NORMAL PORTLAND CEMENT TYPE I			MODERATE HEAT PORTLAND CEMENT TYPE II		HIGH EARLY STRENGTH PORTLAND CEMENT TYPE III	
		*	A.S.T.M. C150	FEDERAL SS-C-192	A.S.T.M. C150	FEDERAL SS-C-192	A.S.T.M. C150	FEDERAL SS-C-192
CHEMICAL								
Silica (SiO_2)		Min.%			21.0	21.0		
Alumina (Al_2O_3)		Max.%		7.5	6.0	6.0		7.5
Ferric Oxide (Fe_2O_3)		Max.%		6.0	6.0	6.0		6.0
Lime (CaO)								
Magnesia (MgO)	2.5	Max.%	5.0	5.0	5.0	5.0	5.0	5.0
Sulfuric Anhydride (SO_3)								
When $3CaO.Al_2O_3$ is 8.0% or less		Max.%	2.0	2.0	2.0	2.0	2.5	2.5
When $3CaO.Al_2O_3$ is greater than 8.0%	1.9	Max.%	2.5	2.5			3.0	3.0
Ignition Loss	0.88	Max.%	3.0	3.0	3.0	3.0	3.0	3.0
Insoluble Residue	0.14	Max.%	0.75	0.75	0.75	0.75	0.75	0.75
Ratio, Al_2O_3 to Fe_2O_3					0.7 - 2.0			
Potential Compounds								
Tricalcium Silicate ($3CaO.SiO_2$)		Max.%			50	50		
Tricalcium Aluminate ($3CaO.Al_2O_3$)		Max %		15	8	8	15	15
PHYSICAL								
Fineness, Specific Surface, (Wagner)	1650	Min.	1600	1600	1700	1800		
Soundness, Autoclave Expansion	0.26	Max.%	0.5	0.5	0.5	0.5	0.5	0.5
Time of Set (Gillmore)								
Initial (Hr. : Min.)	2:45	Min.	1:0	1:0	1:0	1:0	1:0	1:0
Final (Hr. : Min.)	4:50	Max.	10:0	10:0	10:0	10:0	10:0	10:0
Tensile Strength, psi. (*Alternative requirements in italics.*)								
1-day		Min.					275	
3-day	356	Min.	150		125		375	
7-day	450	Min.	275		250			
Compressive Strength, psi.								
1-day		Min.					*1250*	1250
3-day	1820	Min.	*900*	900	*750*	750	*2500*	2500
7-day	3083	Min.	*1800*	1800	*1500*	1500		(a)

(a) Effective only when so specified by purchaser. Strengths at any age higher than strengths at next preceding specification age.

NOTE:—All test specimens were made and stored under strictly controlled temperature conditions. All testing equipment used complies with the requirements of A.S.T.M. and Federal Specifications for Portland Cement.

Bin test report

1 - Mr. J. A. Wise, Associate Professor of Civil Engineering
University of Minnesota; Minneapolis, Minnesota

Date November 12, 1947 Chemist Boyd H. Walter

Figure 19. Mill Certificate of Portland Cement

flow table exhibited an average flow of 96.43 per cent while the standard value is 108 per cent, hence all readings were corrected by applying the correction factor 1.25. Immediately after measuring the flow, a mortar retentivity test was made in accordance with Federal Specification for Masonry Cement SS-c-181b. Nine two-inch cubes were made from each batch of mortar. These were cured 28 days in a moist room and then tested in an Emery-Southwork hydraulic testing machine. The results of the mortar tests are summarized in Table II.

Table II. Average Properties of Mortar

Portland cement, parts by volume	1
Lime, parts by volume	1.01
Sand, parts by volume	5.18
Water, per cent of dry weight of mortar ingredients	21.8
Flow, per cent	105
Retentivity, per cent	52
Ultimate compressive strength, pounds per square inch	1,212

The retentivity was slightly lower than desirable, but it was impossible to secure higher retentivity without changing either the mix or the water content. The mortar chosen represented the

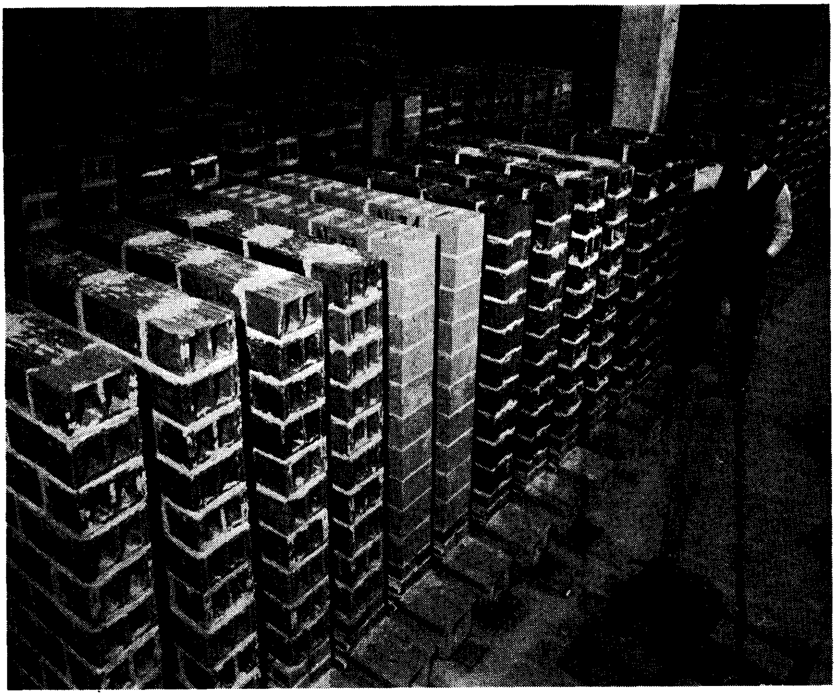


Figure 20. Test Panels in Laboratory

best compromise which was satisfactory to the mason. A standard brand of Portland cement was used. Its mill certificate is shown in Figure 19. For the first eight panels a standard hydrated lime was used, and for all others a pressure hydrated lime was used.

Fifty-six panels, consisting of 28 pairs of similar panels, were built. They were cured in the laboratory, and they were sprinkled with water twice daily for the first seven days because the humidity in the laboratory was very low. For lifting and moving the panels, a pair of hydraulic lift trucks with solid rubber tires was used. These may be seen in Figure 21.

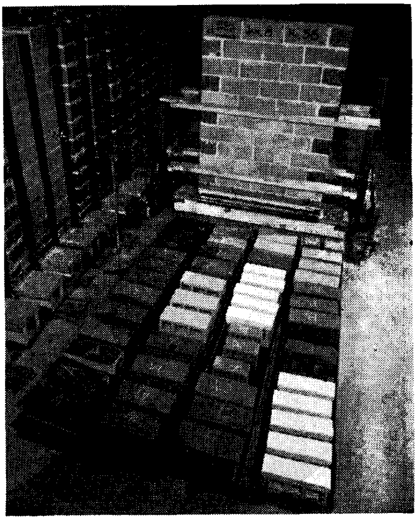


Figure 21. Test Panels and Lift Truck

TEST RESULTS

Tests of Tile

All the tile were tested, using five representative specimens of each type, for 24-hour cold water absorption, five-hour boiling absorption, suction, capillarity, and crushing strength. The results of these tests are shown in Table III.

These tests were made in conformity with the provisions of ASTM Standard Designation C 112-36 *(55)* and ASTM Designation C 67-44, modified so as to be applicable to clay tile.

Permeability Tests of Panels

About 45 to 60 days after the panels were built, they were placed in a special testing frame, Figures 22 and 23, in a moist room. This testing frame is similar to that used by the National Bureau of Standards in its tests *(29)*. Two moist rooms and four testing frames were used. In the side construction panels, the ends of the panels were closed with sheets of ordinary double strength window glass, wedged in place against a plastic caulking compound. Each moist room had a recording thermo-humidgraph, and, during tests, the relative humidity was kept at 80 to 90 per cent. The water supplied to the faces of the panels was heated in a tank with temperature controls to about 70 F. A gallon glass jar containing fluorescein in solution was placed over

Table III. Tests of Tile

Tile	Capillarity Rise, Inches			Suction, gms/cm^2		Absorption, Per Cent		C/B	Compressive strength, lbs/in.^{2}	
	1 hr	24 hr	168 hr	1 min	5 min	24-hour cold water (C)	5-hour boiling (B)		Gross area	Net area
a	0.26	0.28	0.29	0.014	0.033	3.45	3.48	0.99	661	1,854
A	0.32	0.36	0.38	0.021	0.027	2.02	2.26	0.89	479	1,228
b	0.55	0.84	0.92	0.030	0.045	9.33	12.57	0.74	565	1,159
B	0.42	0.45	0.47	0.037	0.075	7.92	8.27	0.96	626	2,359
c	0.27	0.27	0.30	0.025	0.041	3.08	2.95	1.04	1,092	2,786
d	0.88	1.13	2.84	0.018	0.024	8.70	8.81	0.99	554	1,425
e	1.08	3.19	7.03	0.054	0.086	6.41	6.62	0.97	3,678	5,840
E	1.09	3.60	5.74	0.039	0.074	6.60	6.62	1.00	3,593	7,017
g	0.57	1.09	1.13	0.016	0.020	8.64	8.77	0.99	1,084	2,500
h	0.44	0.47	0.49	0.019	0.028	7.01	7.08	0.99	3,272	5,880
m	0.72	0.82	0.91	0.013	0.022	2.32	2.47	0.94	2,930	5,906
p	0.47	0.84	3.03	0.016	0.025	3.43	3.59	0.96	4,503	6,103
R	0.74	0.84	0.97	0.009	0.013	0.99	1.05	0.94	5,440	10,246
t	0.73	1.04	1.09	0.028	0.033	2.62	2.73	0.96	2,640	4,297
v	0.48	0.49	0.51	0.017	0.025	4.06	4.28	0.95	3,297	8,232

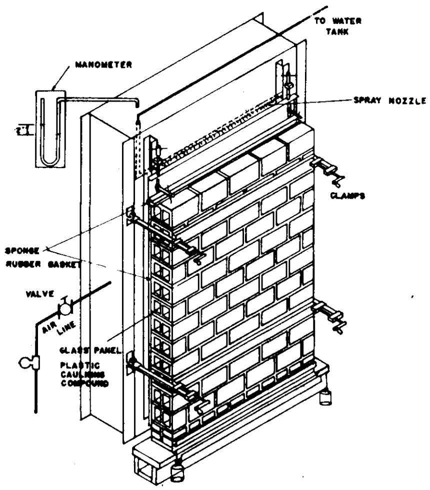


Figure 22. Typical Wall in Test Chamber

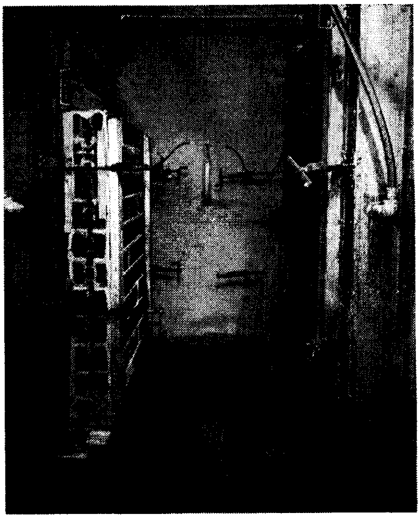


Figure 23. Testing Frames and Panel in Moist Room

the tank and arranged so that the water could be dosed with the solution.

Each panel was given a 24-hour permeability test. Water was supplied to the face of the panel, and an air pressure of two inches of water was applied continuously. A heavy dosage of fluorescein was supplied for the first two or three hours of this test. Mimeographed diagrams of the backs of the panels were used to record the time and the points at which free water first was noted. The free water was determined by visual inspection of the backs of the panels under ultraviolet light. Even a very minute drop of free water could be detected easily by this means. The rate of free water coming through the flashings was observed by timing the flow collected in beakers and measuring it. Observations were also made, on side construction panels, of water collected in cells inside the panel. These observations were greatly aided by the use of the ultraviolet light and the fluorescein dye.

By looking through the glass in the side construction panels during the early part of the test, the movement of water within could be easily seen. In many cases, a fine stream of water could be seen squirting into the cells from the face of the panel at the junction of mortar and tile at the joints. It was clear that the water, in some cases, started to come through almost immediately and that it was finding a passage along the interfaces between mortar and tile. The flow through horizontal joints was noted, but its progress could not be followed as clearly since the tile cells soon started to fill up. The distribution of points through which water started to pass was apparently quite random. In many cases, several tiers of cells would start to collect water, and sometimes some cells were almost completely filled with water at the end of 24 hours. Other tiers of cells would remain absolutely dry, or almost so, even though cells above and below were full of water. The water would enter a tier of cells at one or more points, start to fill the cells, and then, at some other point or points on the inner face of the panel, start to leak through that face. The bed joints appeared to be more resistant to the passage of water than the head joints. The water which finally reached weep holes and flashing in the base was chiefly water coming through the faces of tiers close to the bottom. Thus, the measure of rate of flow from the flashings was not a good comparative measure, particularly when side and end construction types were compared.

In the end construction panels, the tops were left open and covered only with a loose piece of plywood to protect them against moisture and condensation from the moist room. In these panels, the passage of water could also be seen by looking into the cells from above. A similar random distribution of fine streams of water was noted coming through these joints. However, the water did not collect in the cells but drained vertically to weep holes in the base. The panels were weighed before this test, and, after the test, they were removed from the moist room and placed in the laboratory. There they were dried until their weights were substantially the same as before the test. Then they were returned to the moist room and the permeability test was repeated for five days. Just before completion of the five-day tests, a heavy dose of fluorescein was again used in each panel.

After the permeability tests were completed, the panels were dried and carefully taken apart. In some cases the mortar joints were stronger than the tile, and it was difficult to find any trace of moisture passage. In most cases, however, water had passed through the panel, as indicated by pink deposits of fluorescein. Samples of tile and mortar after the tests are shown in Figures 24 and 25. In every case, the water had passed along an interface between mortar and tile. It is also very clear that the passages occurred where there was some deficiency in bond between the two. No appreciable passage of water through the mortar was seen, and no cracks were found in the mortar away from the interfaces.

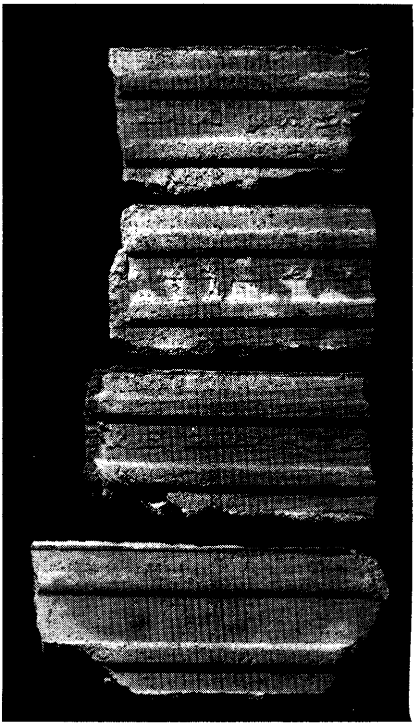


Figure 24. Samples of Mortar after Tests

Figure 25. Samples of Mortar and Tile after Tests

The results of these permeability tests are shown in Table IV. The ratings in the table were determined by the following formulas:

For 24-hour permeability tests,

$p = 100 - (p_1 + p_2 + p_3 + p_4 + p_5)$

where p = final rating in per cent,

p_1, p_2, p_3, p_4, p_5 = percentages to be deducted as shown below, and

100 = perfectly impermeable wall.

$p_1 = 24 - t_1$

where t_1 = time in hours for first free water to appear.

$p_2 = \frac{1}{4}(24 - t_2)$

where t_2 = time in hours for first dampness to appear.

$p_3 = 30\,(1_1)^{\frac{1}{3}}$

where 1_1 = ratio of total length of joints showing free water to total length of all mortar joints.

$p_4 = 10\,r$

where r = ratio of area showing dampness to total area of panel. This includes areas showing free water.

$$p_5 = 30 - \sqrt{\frac{112500}{f + 125}}$$

where f = rate of flow from flashings (top and bottom) in cubic centimeters per hour measured either at the end of the 24-hour test or when the flow is greatest.

For five-day permeability tests, the rating method was similar, but it was arranged to avoid duplication of 24-hour results. For these, the final rating in per cent was,

$$p = 100 - (p_3 + p_4 + p_5 + p_6)$$

where p_3, p_4, and p_5 are as previously defined (except that for p_5, f is the final rate of flow from flashings at the end of the five-day test), and

$$p_6 = 30 - \sqrt{\frac{112500}{g + 125}}$$

where g = maximum rate of flow from flashings in cubic centimeters per hour.

In order to combine the 24-hour ratings and the five-day ratings on a comparable basis, both ratings were reduced to a mean rating of 50, and the mean of this reduced rating is given as the average. Calling r_1 the 24-hour rating, R_1 the mean rating of all panels on 24-hour test, r_2 the 120-hour rating, and R_2 the 120-hour mean rating for all panels, the reduction in each case was produced by the transformation,

$$x = ar^n$$

where x = rating converted to a mean of 50,

$$n = \frac{\log 2}{\log \frac{100}{R}}$$

$$a = 100^{1-n}$$

using appropriate subscripts for each test group. The final average rating is then $\frac{1}{2}(x_1 + x_2)$.

Table IV. Results of Permeability Tests

Panel No.	Tile Design	Type of Construction	Permeability Ratings 24-hour	5-day	Average
1	c	FTS, solid shell, standard side construction, divided bed	44	34	42
2	A	FTS, double shell, heavy duty, side construction, divided bed	34	46	43
3	A	FTS, double shell, heavy duty, side construction, divided bed	57	81	69
4	a	FTX, solid shell, standard, side construction, flat bed	47	69	59
5	b	FTS, cored shell, heavy duty, side construction, divided bed	71	86	78

Table IV. Results of Permeability Tests—Continued

Panel No.	Tile Design	Type of Construction	Permeability Ratings		
			24-hour	5-day	Average
6	a	FTX, solid shell, standard, side construction, flat bed	45	49	49
7	b	FTS, cored shell, heavy duty, side construction, divided bed	34	28	34
8	c	FTS, solid shell, standard, side construction, divided bed	*	*	*
9	e	FTX, double shell, heavy duty, end construction, recessed end	74	71	74
10	E	FTX, double shell, heavy duty, end construction, recessed end	81	35	62
11	e	FTX, double shell, heavy duty, end construction, recessed end	83	65	77
12	E	FTX, double shell, heavy duty, end construction, recessed end	64	14	42
13	g	FTS, double shell, standard, side construction, divided bed	45	34	42
14	g	FTS, double shell, standard, side construction, divided bed	88	69	81
15	d	FTS, double shell, heavy duty, side construction, flat bed	85	70	80
16	d	FTS, double shell, heavy duty, side construction, flat bed	57	40	51
17	h	FTX, solid shell, standard, end construction, plain end	49	30	42
18	h	FTX, solid shell, standard, end construction, plain end	30	19	27
19	d	FTS, double shell, heavy duty, side construction, flat bed	66	22	44
20	d	FTS, double shell, heavy duty, side construction, flat bed	46	33	42
21	d	FTS, double shell, heavy duty, side construction, flat bed	36	46	44
22	d	FTS, double shell, heavy duty, side construction, flat bed	39	28	36
23	d	FTS, double shell, heavy duty, side construction, flat bed	49	42	48
24	d	FTS, double shell, heavy duty, side construction, flat bed	41	33	40
25	d	FTS, double shell, heavy duty, side construction, flat bed	41	30	38
26	d	FTS, double shell, heavy duty, side construction, flat bed	68	30	52
27	d	FTS, double shell, heavy duty, side construction, flat bed	52	45	51
28	d	FTS, double shell, heavy duty, side construction, flat bed	64	34	52

* Panel leaked excessively and could not be tested.

Table IV. Results of Permeability Tests—Continued

Panel No.	Tile Design	Type of Construction	Permeability Ratings		
			24-hour	5-day	Average
29	d	FTS, double shell, heavy duty, side construction, flat bed	73	53	66
30	d	FTS, double shell, heavy duty, side construction, flat bed	44	58	53
31	d	FTS, double shell, heavy duty, side construction, flat bed	64	48	59
32	d	FTS, double shell, heavy duty, side construction, flat bed	47	67	58
33	v	FTX, solid shell, heavy duty, end construction, plain end	87	*	85
34	v	FTX, solid shell, heavy duty, end construction, plain end	90	*	89
35	m	FTX, double shell, standard, end construction, recessed end	58	34	49
36	m	FTX, double shell, standard, end construction, recessed end	63	31	50
37	d	FTS, double shell, heavy duty, side construction, flat bed	58	48	55
38	d	FTS, double shell, heavy duty, side construction, flat bed	51	42	49
39	d	FTS, double shell, heavy duty, side construction, flat bed	57	47	54
40	t	FTS, cored shell, heavy duty, end construction, recessed end	85	47	70
41	t	FTS, cored shell, heavy duty, end construction, recessed end	81	42	65
42	p	FTS, solid shell, heavy duty, end construction, plain end	6	3	6
43	p	FTS, solid shell, heavy duty, end construction, plain end	31	16	26
44	B	FTS, solid shell, standard, side construction, flat bed	26	18	24
45	B	FTS, solid shell, standard, side construction, flat bed	27	14	22
46	d	FTS, double shell, heavy duty, side construction, flat bed	27	10	20
47	d	FTS, double shell, heavy duty, side construction, flat bed	41	30	38
48	R	FTX, double shell, heavy duty, end construction, plain end	94	48	75
49	R	FTX, double shell, heavy duty, end construction, plain end	61	*	56
50	d	FTS, double shell, heavy duty, side construction, flat bed	32	16	26
51	d	FTS, double shell, heavy duty, side construction, flat bed	48	54	53

* Panel leaked excessively and could not be tested. Rating, 50 per cent of 24-hour test.

Table IV. Results of Permeability Tests—Continued

Panel No.	Tile Design	Type of Construction	Permeability Ratings 24-hour	5-day	Average
52	d	FTS, double shell, heavy duty, side construction, flat bed	61	74	68
53	d	FTS, double shell, heavy duty, side construction, flat bed	32	15	26
54	d	FTS, double shell, heavy duty, side construction, flat bed	85	42	68
55	d	FTS, double shell, heavy duty, side construction, flat bed	56	31	46
56	d	FTS, double shell, heavy duty, side construction, flat bed	34	24	32

The mean score for the 55 panels tested was 50, and the R.M.S. deviation from the mean was 18. This indicates a fairly significant spread of the scores. On comparing pairs of similar panels, of which there were 27, the R.M.S. deviation from the mean of each pair was 10 and the probable error was seven. Hence we conclude that deviations from the mean greater than seven are probably significant.

The following comparisons of scores were found:

	Mean Score
Type of Shell	
Solid shell	44
Double shell	60
Cored shell	62
Side vs. End Construction	
Side construction	52
End construction	54
Side Construction, Bed Type	
Flat bed	48
Divided bed	56
End Construction, End Type	
Plain end	46
Recessed end	61
FTX vs. FTS	
FTX	57
FTS	49
Standard vs. Heavy Duty	
Standard	44
Heavy duty	58

	Mean Score
Admixtures and Treatments	
Standard panel	51*
Admixtures	
Brickron	49
Hydratite	59
Mortite	59
Vinsol resin	44
Mortar mix	40
Treatments	
28-day moist room curing	45
Mortar retempered	53
Mortar wet as possible	61
Mortar dry as possible	47
Mortar standing five hours	33
Mortar laid in freezing weather	38
Open space left in head joint	39

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* Only one panel used for comparison. The other panel had an unusually high score and was rejected from the scoring.

Supplementary Tests

After the first panels had been taken apart and the passage of water had been noted, two additional panels were built using tile "d." In these panels, the surfaces of all tile in contact with mortar were first given a brush coat of neat Portland cement mixed to the consistency of thick paint. The object of this treatment was to provide better bond and to determine whether such improved bond would prevent the passage of water. To show whether this treatment depended upon quality of workmanship also for its effectiveness, one panel was made using amateur workmanship and the other using expert workmanship. It was not possible to do any more research in this direction because

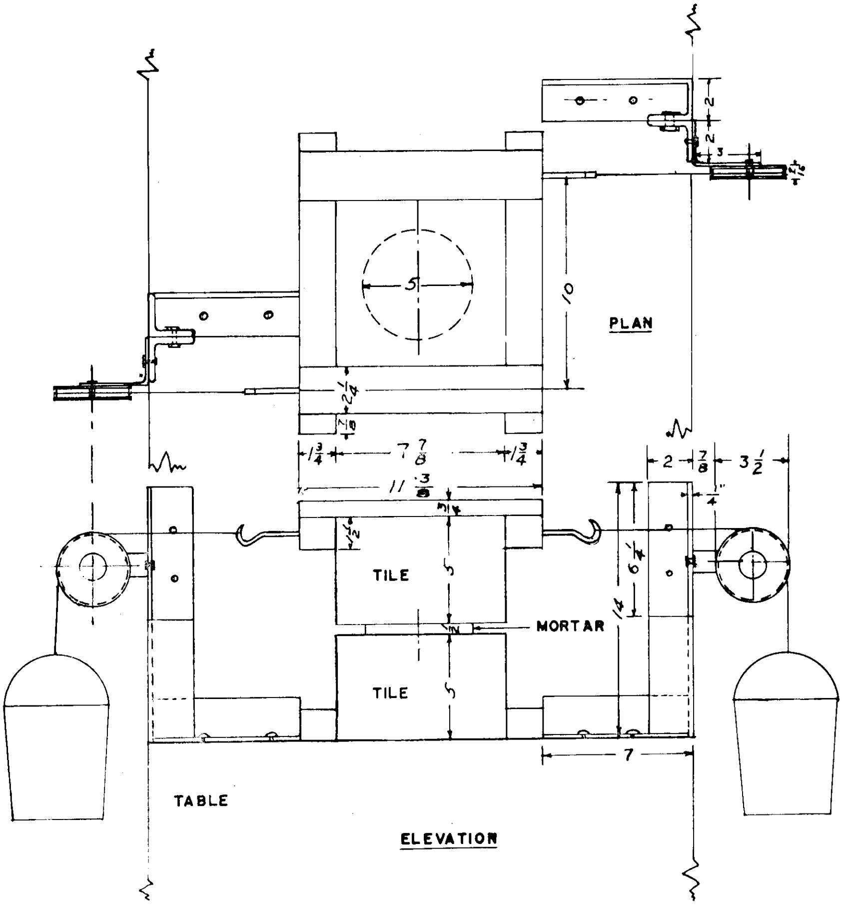

Figure 26. Bond Testing Apparatus

of the lack of time and funds to complete the work under the contract.

The results of the tests are shown by the following ratings:

Panel No.	Permeability Ratings		
	24-hour	5-day	Average
57 (amateur workmanship)	*	*	*
58 (expert workmanship)	42	51	49

* Panel 57 leaked excessively and could not be tested.

A suggested method of making bond strength tests of tile and mortar is indicated in Figure 26. A pure torsion is applied by this apparatus to a cylinder of mortar five inches in diameter. The apparatus was built and found to work quite well.

SUMMARY AND CONCLUSIONS

1. Under conditions similar to those of the tests, which are intended to simulate rain driven by wind, water passes through interfaces between mortar and tile. When tile are highly absorptive and have thin shells, water may pass through tile walls after four or five days of continuous testing, but to a lesser degree than through interfaces at joints.

2. Double shell and cored shell constructions were significantly less permeable than single shell; heavy duty and FTX were somewhat less permeable than standard and FTS. End construction was slightly better than side construction, and end construction with recessed ends was significantly better than any side construction. Side construction with divided bed was slightly better than side construction with flat bed.

3. There was no apparent correlation between absorption of tile and permeability. There was an apparent inverse correlation between tile capillarity and wall permeability, that is, tile of high capillarity tended to be low in permeability.

4. The use of integral waterproofing compounds, plasticizing agents such as vinsol resin, and the use of ground clay to replace lime were found to be of no appreciable value, and in some cases they increased the permeability of the wall.

5. Various treatments such as curing in a moist room, using retempered mortar, using divided head joint in mortar in side construction, and using very wet or very dry mortar seemed to produce very little significant effect on water permeability. Walls laid in freezing weather and walls constructed with partially set, stiffened mortar were more permeable, but the difference was not too great.

6. The preceding results can be interpreted in terms of the bond between tile and mortar. In all cases, the thicker-walled tile would have more area to which mortar could adhere and less likelihood of water finding interfacial passages. The FTX tile having better formed, more regular and flatter surfaces would probably bond better. The surface texture of the tile, which is somewhat related to its capillarity, would influence the bond. Very smooth, semiglazed surfaces would occur in tile with low capillarity and would be likely to have poorer bond than the rougher surfaces which would occur in tile with higher capillarity.

7. In side construction walls, water penetrating one face tends to fill the cells and, thus, tends to find opportunities for passing through the other face. Where divided beds are used in side construction, there is some opportunity for water to find passage downward through the walls, and this may account for their slightly better performance. End construction walls allow free passage downward for water coming through one face, and, if drainage is provided at the bottom of the wall, leakage through the wall would tend to be reduced. Recessed ends seem to reduce leakage.

8. The application of Portland cement paint on tile surfaces just prior to placing the mortar did not produce any significant change in the permeability of the wall.

RECOMMENDATIONS

For structural clay tile facing walls of minimum water permeability, it is recommended that double or cored shell, FTX, heavy duty, end construction be employed. A dense, well-graded mortar, good workmanship, and reasonable curing conditions are recommended. Attention should be concentrated upon securing well-filled mortar joints, using tooled joints, and obtaining perfect bond at all mortar-tile interfaces. Care should be exercised in handling tile so that no oil, grease, or other bond inhibiting impurities adhere to the tile. Glazed or semiglazed surfaces should be avoided. Retempered mortar may be used if not too old and if rendered plastic. The flow of the mortar is not highly important. The use of integral waterproofing compounds, air entraining compounds and ground clay is not recommended.

For future research, it is recommended that factors affecting bond of mortar and tile and methods of improving this bond be studied. It appears probable that almost any type of construction having reasonably good wall thickness might be made impermeable if the bond between mortar and tile could be rendered almost perfect. As a means of measuring this bond, a test based upon the suggested torsion test might be used. Suggested methods of improving the bond are the use of cleaning agents on the surface of the tile, the use of cement or other adhesive coatings, the improvement of mortar characteristics, the use of admixtures in mortar to improve the bond, and the roughening of the surface of the tile. The construction of a building using structural clay tile facing walls made as impermeable as possible after the above studies have been made, and in a location where heavy rains driven by strong winds occur, might be an excellent way of testing these theories in practice.

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