PROGRESS REPORT ON INVESTIGATION OF FIRE-CLAY BRICKS AND THE CLAYS USED IN THEIR PREPARATION[1]

By R. A. Heindl and W. L. Pendergast

ABSTRACT

This is a progress report of an extensive study of fire clays and fire-clay bricks. It includes the results of a preliminary study of clays representative of those used in the manufacture of refractories throughout the United States. Chemical analyses and a summary of physical tests are given of both fire clays and the bricks manufactured from them. The thermal expansion behavior of the fire clays fired at 1,400° C. and those of the fire bricks "as received" from the manufacturer and also after firing at 1,400°, 1,500°, and 1,600° C. were studied and the materials classified into groups having characteristic thermal expansions. The moduli of elasticity and rupture were determined at 20°, 550°, and 1,000° C. The resistance of the brick to spalling in a water-quenching test is expressed in an empircal relation correlating the elasticity, strength, coefficient of expansion, and percentage of grog used in compounding the brick batches. Data are presented on individual bricks made by the same manufacturer showing probable reasons for great differences in the number of quenchings required to cause spalling in the water-dip test.

CONTENTS

[1] A preliminary report of this investigation has appeared as Technologic Paper No. 4 of the American Refractories Institute.

I. INTRODUCTION

An extensive study was undertaken in the summer of 1926 of the representative clays and grogs used in the manufacture of clay refractories in the principal producing districts of the United States. The program outlined for this investigation includes the following studies of the fire clays and fire-clay refractories:

1. Their chemical and petrographic analyses.
2. Determination of their elastic deformation under load at room temperature, 550° and 1,000° C.
3. Observation of linear thermal dilatation.
4. Investigation of the effect of temperature on certain physical properties.
5. The effect on the finished refractory of grog fired at different temperatures, the amount and grading, and what the effect may be, whether it is crushed or ground.
6. Reactions at high temperatures of the clay refractories with typical slags.

It is also planned to make a comparison of the properties of the commercially prepared fire bricks and fire bricks made in the laboratory, using commercial batches. A study of the properties of blended clays, similar to that itemized above, is also contemplated.

The laboratory testing of fire-clay refractories to determine those properties which are believed to be directly related to the life of a refractory in service, as emphasized in recent publications by Geller [2] and Phelps,[3] has led to the conclusion that more data on properties other than those already generally investigated were essential. Producers of refractories are aware that the method of manufacture employed greatly affects the physical properties of the finished product. They do not know, except in a general way, either the qualities of the individual clays, raw or fired, or their relation to the properties of the final product in which they may be used. There can be little doubt that the physical properties of a refractory are affected, not only by the texture and composition of the clays and grog entering into its manufacture but also by the relation of the qualities of the blended clays, and the grogs and clays, to each other. Unless the properties of the individual clays entering into a blend are known, no conception is possible as to whether the finished product is in a highly strained state or whether during heating and cooling internal stresses are set up which may cause rupture between individual particles having different properties and eventually cause failure of the refractory.

The purpose of this work is therefore to obtain data which will lead to a better understanding of the interdependence of raw materials and manufacturing methods. It would seem evident that a knowledge of the important characteristics of the fire clays, how they are altered when subjected to different temperatures, the effect of one clay on another when blended, and how these characteristics are affected by the physical structure of the manufactured product should prove of great value in assisting the producer of fire-clay refractories to choose those clays most desirable for a particular product or a product used for a particular purpose.

II. GENERAL INFORMATION ON MATERIALS

The materials for this study have been furnished by 12 manufacturers of refractories. They include 17 different brands of fire bricks, several hundred pounds each of 26 clays used in the manufacture of these bricks, prepared grog, and green batch. With one exception, detailed information as to the composition of the batch, method of manufacture, and temperature of firing was also furnished. The clays are: 7 flint, 4 semiflint, 12 plastic, and 3 miscellaneous. The last are so classified because they can not be properly placed with clays of the

[2] B. S. Tech. Paper No. 279, Testing of Fire-Clay Brick With Special Reference to Their Use in Coal-Fired Boiler Settings.

[3] Properties of Refractories and Their Relation to Conditions in Service, A. S. M. E. Trans., Jan.–April, 1928.

three types mentioned. In addition, three samples of quartz and sand are included.

Each brand of fire-clay brick when received was assigned a key letter so that the 17 brands included in this study are identified with letters A to R, inclusive, but with the letter O omitted. The clays and other materials from which the bricks are manufactured are identified as far as possible with the same key letter as the bricks in which they are used. Since most bricks are made from two or more clays the materials are further identified by a number following the letter; for example, clays A–1 and A–2 are used in the manufacture of fire-clay brick brand A.

Since the nature of the clays and the method of manufacture of fire-clay bricks have a decided influence on the properties and, consequently, the life of the refractory under various conditions of service, it was considered advisable to obtain as much general information as possible on the materials included in this study. In succeeding tables will be found listed the various types of clays or other materials entering into the manufacture of the 17 brands of fire brick, the location from which they are obtained, and the methods employed in the manufacture of the various brands of bricks.

III. METHODS OF TESTING

1. THERMAL EXPANSION

The linear thermal expansions of the fire clays were determined by means of the interferometer.[4] This method was used because a sufficiently representative specimen of fire clay of the small size required could readily be prepared for test purposes. The thermal expansions of the fire bricks were determined by an indirect method [5] with the apparatus shown in Figure 1, on specimens approximately 1 by 1 by 6 inches cut from the brick. Because most fire-clay bricks are composed of one or more fire clays and various precentages of coarse and fine grogs, it is essential to make observations on a large specimen so that the data obtained may be representative of the whole brick. Thermal expansion determinations from 20° [6] to 1,000° C. were made on specimens cut from the bricks, "as received," after reheating for five hours at 1,400° C., 1,500° C., and again after heating three hours at 1,600° C.

2. MODULUS OF ELASTICITY, TRANSVERSE STRENGTH, MAXIMUM ELONGATION, AND PLASTIC FLOW

The apparatus used in observing deflections of the specimens under various loads and determining transverse strength (modulus of rup-

---

[4] Described in B. S. Sci. Paper No. 485.

[5] For a description of the apparatus and method used see J. Am. Ceram. Soc., 9 (9), pp. 555–574; 1926.

[6] Room temperature was approximately 20° C. during these experiments.

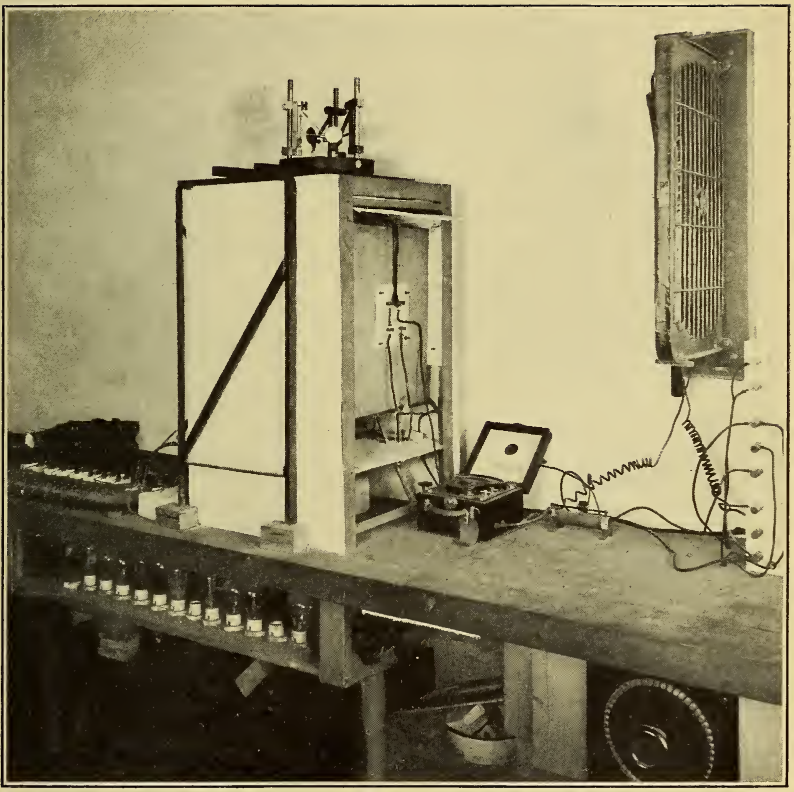

FIGURE 1.—*Furnace and apparatus used in the determination of linear thermal expansions*

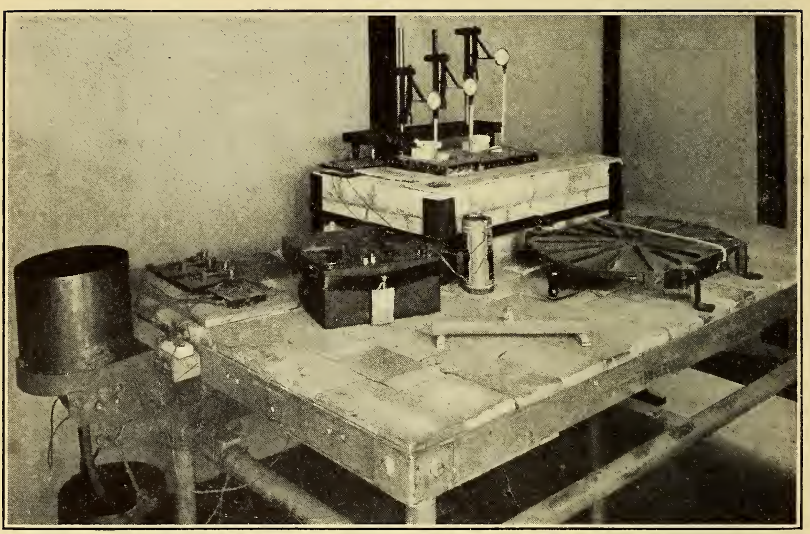

FIGURE 2.—*Apparatus used in determining elastic and plastic flow properties of fire-clay bricks*

ture) is shown in Figure 2, and a detailed description of it and the method for determining the load-deflection curves are given in the Third Progress Report of the Sagger Investigation.[7] The modulus of elasticity and modulus of rupture were determined at several temperatures, the former from the load-deflection curve and the latter using the load which broke the specimen. The values of the maximum elongation were computed by dividing the modulus of rupture by the modulus of elasticity.

The plastic flow at 1,000° C. of the various brands of fire bricks was determined with the same apparatus as was used to determine the elasticity and breaking strength. The plastic flow of the material under any particular stress increment was considered as the "set" or difference between the deflection caused by the load and the recovery of the material on removal of this load. A detailed description of the method for determining this property is given in the Fourth Progress Report of the Sagger Investigation.[8]

3. THERMAL-SPALLING TEST

The spalling test was made on five bricks which had been reheated at 1,400° C. for five hours. The general procedure followed is described in United States Government Master Specification for Fire-Clay Brick.[9] The test requires one end of the brick to be heated in the door of a suitable furnace maintained at 850° C. At hourly intervals the hot end of the brick is immersed in running water to a depth of 4 inches for three minutes. After removing and allowing the specimen to steam in the air for five minutes, the cycle is repeated until the entire end of the brick has completely spalled.

A somewhat modified form of the foregoing spalling test was introduced to permit of some comparison of results obtained on bricks tested under different conditions. Samples of the several brands of brick "as received" were placed in the door of a laboratory kiln so that one end of each brick received the prescribed reheating for five hours at 1,400° C., the other end being exposed to room temperature. The test was otherwise conducted in the same manner as that described above, except that the reheated end of the brick was immersed in water to a depth of 2 instead of 4 inches.

4. SOFTENING POINT TEST (PYROMETRIC CONE EQUIVALENT)

The softening-point (P. C. E.) test was carried out according to the method approved by the bureau, and known as the A. S. T. M. standard method, serial designation C24–20.

---

[7] J. Am. Ceram. Soc., **10** (7), pp. 524–534; 1927.
[8] J. Am. Ceram. Soc., **10** (12), pp. 995–1004; 1927.
[9] B. S. Circular No. 299.

5. CHEMICAL ANALYSES

In making the chemical analyses of the fire clays and fire-clay bricks, the procedure followed was, in general, the method of analysis for refractories described by Lundell and Hoffman.[10]

6. SUPPLEMENTARY STUDIES

The absorption of the bricks was determined "as received" from the manufacturer and also after refiring at 1,400° C. for five hours. The samples after being dried and weighed were boiled for four hours and permitted to remain in the water approximately 18 hours, after which the saturated weight was determined. The absorption, expressed in per cent, was computed by dividing the weight of water absorbed by the weight of the dry-test piece.

The various sizes of the grog in the green batch materials furnished by the several manufacturers were determined on a 500 g sample previously dried for approximately 24 hours at 110° C. After drying, sieve analysis of the sample was made by the wet method.

Petrographic examinations were made on three flint and three semiflint unfired clays.

IV. RESULTS

1. PETOGRAPHIC EXAMINATIONS[11]

Petrographic examination of the several flint and semiflint clays included in the investigation gave the following information:

Sample D–1. Missouri semiflint. "North Missouri."

(*a*) A clay mineral (kaolinite or leverrierite) is abundant, but in exceedingly fine plates.

(*b*) Isotropic (amorphous, colloidal aggregates?) material is present, but it is difficult to estimate quantity, probably less than in C–1.

(*c*) Quartz is probably somewhat coarser grained than in C–1 and is very abundant, probably more than 40 per cent.

(*d*) Minor constituents are present in small quantities. No rutile (TiO_2), siderite ($FeCO_3$) or rhodochrosite ($MnCO_3$) was observed.

Sample Q–1. Missouri flint clay.

(*a*) Consists largely of a clay mineral in fine grains and amorphous, isotropic material.

(*b*) No carbonates, such as siderite or rhodochrosite, are present.

(*c*) Quartz is present only in small amounts, probably less than 5 per cent.

(*d*) A few grains of a mineral of very high index were observed, possibly a titanium compound.

Sample B–1. Pennsylvania semiflint.

(*a*) A clay mineral (kaolinite or leverrierite) in minute plates is abundant.

(*b*) Isotropic (amorphous, colloidal aggregates?) material is somewhat less abundant than (*a*).

---

[10] Analysis of Bauxite and of Refractories of High Alumina Content, B. S. Jour. Research, 1, (RP5); July, 1928.

[11] Petrographic examinations made by H. Insley.

(*c*) Siderite or rhodochrosite is present in small amount, probably less than 5 per cent.

(*d*) Fairly coarse-grained quartz is present in small amounts, less than 10 per cent.

(*e*) There are other minor constituents, such as Fe_2O_3, TiO_2, etc.

Sample C–1. Pennsylvania flint.

(*a*) A clay mineral (kaolinite or leverrierite) in minute plates is slightly less abundant than in B–1.

(*b*) Isotropic (amorphous, colloidal aggregates?) material, index about 1.57, often containing particles of (*a*), is slightly more abundant than in B–1.

(*c*) Siderite or rhodochrosite is more abundant than in B–1, but there is probably less than 10 per cent present.

(*d*) Quartz is fairly fine grained, and in somewhat larger amounts than in B–1.

(*e*) A small amount (less than 2 per cent) of what appears to be rutile is present.

Sample I–1. Kentucky semiflint.

(*a*) A clay mineral is abundant, but occurs in small plates.

(*b*) Isotropic material is apparently not as abundant as in previous samples.

(*c*) No siderite or rhodochrosite was observed. One or two grains of calcite are present, probably less than 2 per cent.

(*d*) Nearly as much quartz is present as in D–1. It is decidedly coarser grained, but still of microscopic dimensions (maximum size about 0.15 mm; average size estimated at 0.05 mm).

(*e*) Apparently less of the minor constituents are present than in the other samples.

Sample K–1. Kentucky flint.

(*a*) Clay minerals occur as extremely minute plates. Probably a smaller amount present than in any other of the samples examined.

(*b*) Isotropic (amorphous, colloidal aggregates?) material with index about 1.57 is probably more abundant than in other samples.

(*c*) A small amount of siderite or rhodochrosite, probably less than 2 per cent, is present.

(*d*) There is very little quartz present, probably less than 5 per cent.

(*e*) Minor constituents are present in small amounts.

2. CHEMICAL ANALYSES [12]

The chemical analyses of the fire clays are given in Table 1 and that of the fire-clay brick in Table 2.

A study of the data shows a wide variation in the composition of these materials. As shown by the analyses of samples H–3, H–4, and P–1 (Table 1), these materials are composed largely of silica.

The mineralogical constitution of the several brands of fire bricks, as computed from their chemical analyses,[13] are shown in Table 2. Only two of the brands (C and Q) show an excess of alumina, although a number of brands show only a slight excess of uncombined quartz. The flux content, which appears to be rather high in a number of cases, may be partially attributed to the percentage of titanium oxide present, which was overlooked in some earlier analyses of fire-clay refractories.[13]

[12] Chemical analyses made by J. F. Klekotka.

[13] B. S. Tech. Paper No. 279 describes in detail the method used.

TABLE 1.—*Chemical analyses of fire clays*

Laboratory key letter	Ignition loss	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Total
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
A-1	14.30	43.32	35.72	3.26	2.02	0.18	0.40	99.20
A-2	14.08	44.64	35.84	2.39	1.77	.26	.52	99.50
B-1	13.26	43.38	37.97	1.39	2.12	------	.31	98.43
B-2	14.58	43.06	37.84	2.14	1.84	.12	.04	99.62
B-3	8.16	58.68	24.95	2.39	1.70	.19	.70	96.77
C-1	13.78	42.74	39.18	1.01	2.33	------	.29	99.33
C-2	10.86	50.38	30.87	2.56	2.27	.32	.30	97.56
D-1	12.34	51.82	32.09	1.24	1.63	------	.58	99.70
E-1	14.06	45.98	37.12	.88	1.90	.12	.29	100.35
G-1	14.32	47.09	36.25	.75	1.89	.44	.06	100.80
H-1	7.42	70.29	19.46	.88	2.02	.22	.03	100.32
H-2	14.36	46.36	35.43	1.87	1.57	.44	.46	100.50
H-3	1.62	91.52	4.65	.28	.67	.26	.31	99.31
H-4	2.86	87.68	7.33	1.06	1.25	.38	.14	100.70
H-5	12.82	52.26	32.30	.84	1.72	.26	.02	100.02
H-6	8.14	68.20	21.37	.78	1.63	.34	.12	100.58
I-1	11.62	51.42	32.80	.93	2.33	------	.52	99.62
I-2	13.66	44.66	37.58	1.33	1.53	.66	.15	99.67
I-3	10.62	53.50	29.82	1.95	1.73	.23	.16	98.01
K-1	14.86	42.50	39.68	.76	2.34	------	.12	100.26
K-2	12.28	47.00	33.41	2.59	2.00	.48	.32	98.08
M-1	13.68	44.56	38.19	1.12	2.21	.14	.10	100.00
M-2	11.46	45.76	35.67	1.95	1.72	.30	.64	97.50
P-1	.28	97.48	.72	.14	.46	.16	.32	99.56
Q-1	13.32	42.32	39.63	.84	1.81	.68	.50	99.10
R-1	12.06	52.78	29.90	2.37	1.07	.04	1.20	99.42
R-2	14.66	44.46	37.31	1.13	2.76	.20	.12	100.64
R-3	7.22	72.78	18.94	.65	.61	.23	.14	100.57
T-1	10.92	60.26	25.28	1.62	1.28	.38	.16	99.90

TABLE 2.—*Analyses of fire brick*

Key letter of brand	Chemical analysis							Rational analysis		
	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	CaO	MgO	Ignition loss	Clay	Uncombined quartz	Flux
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
A	40.90	51.48	2.79	2.45	------	0.58	0.24	90.40	2.94	6.66
B	39.08	51.50	3.15	2.53	------	.46	.44	86.80	4.90	8.28
C	43.06	50.00	1.02	2.80	0.54	.41	.26	[1] 93.50	.00	5.96
D	35.31	58.96	1.99	2.02	.50	.30	.16	79.40	15.52	5.10
E	32.11	61.54	1.70	1.89	.50	.29	.40	72.85	21.35	5.70
F	34.54	59.64	1.71	1.97	.52	.63	.26	77.80	16.95	5.18
G	31.91	63.48	1.26	1.97	------	------	.26	71.80	23.10	4.12
H	17.18	80.12	1.02	1.76	.42	.32	.22	40.95	56.52	2.55
I	38.18	54.66	1.89	2.25	.40	.05	.36	85.05	8.62	6.32
J	33.40	57.86	2.26	2.20	.58	1.18	.50	75.60	16.65	7.82
K	36.56	54.98	2.84	2.52	.48	.59	.24	81.81	10.62	7.47
L	39.82	54.00	2.01	2.51	.36	.61	.20	88.22	6.32	5.42
M	38.99	51.56	2.45	2.98	.52	.26	.20	86.65	5.03	8.31
N	34.50	58.44	2.40	2.06	.14	.40	.12	77.78	15.95	6.30
P	27.08	69.12	1.64	1.40	.50	.25	.10	62.42	34.04	3.47
Q	46.76	47.12	1.43	2.45	1.24	.49	.18	[2] 89.40	.00	4.77
R	37.62	56.48	1.96	2.50	.72	.56	.24	83.99	10.82	5.21

[1] 0.52 per cent uncombined Al_2O_3.
[2] 5.86 per cent uncombined Al_2O_3.

3. ABSORPTION

The data on absorption of the bricks "as received" from the manufacturer and also of the bricks after reheating for five hours at 1,400° C. are given in Table 4. The absorption of the specimens "as received" ranges from 5.2 to 17.6 per cent, and for the reheated specimens from 3.0 to 17.1 per cent. Although it is appreciated that firing in a laboratory kiln and firing in an industrial kiln may affect the physical properties of a refractory somewhat differently, the absorption values before and after reheating, as given in the table, give a fair indication of the heat treatment the various fire-clay bricks have received in the manufacturing process.

Data on absorption of fire clays have been determined only after firing the material at 1,160° C. for three hours (cone 4). The data are included in Table 3 simply to make possible a comparison of the clays with one another.

TABLE 3.—*Type of clays—Origin, absorption, and P. C. E.*

Laboratory letter	Type of clay	Origin	P. C. E.	Absorption in per cent of dry weight after firing at 1,160° C. for 3 hours
A-1	Flint	Kentucky	32	11.6
A-2	Plastic	do	32	10.6
B-1	Semiflint	Pennsylvania	33	12.3
B-2	Flint	do	[1] 33	16.7
B-3	Plastic	do	29-30	7.8
C-1	Flint	do	33	16.0
C-2	Plastic	do	30	6.0
D-1	Semiflint	Missouri	31-32	7.7
E-1	do	do	30	13.8
G-1	Plastic		32	26.3
H-1	do	New Jersey	30	20.7
H-2	do	do	32	9.6
H-3	Silica sand	do	32	
H-4	do	do	32	
H-5		do	33	21.0
H-6	Plastic	do	30	20.0
I-1	Semiflint	Kentucky	31	13.0
I-2	Flint	do	33	14.6
I-3	Plastic	Ohio	30	11.5
K-1	Flint	Kentucky	32	17.6
K-2	Plastic	do	32	7.9
M-1	Flint	Pennsylvania	32-33	9.7
M-2	Plastic	do	32-33	22.3
P-1	Crushed quartz	California	33	
Q-1	Flint	Missouri	33	10.7
R-1	Plastic	California	30-31	10.4
R-2	Kaolin	do	32-33	9.2
R-3	Siliceous	do	33	26.1
T-1	Plastic	Illinois	30	8.0

[1] Higher than cone 33.

TABLE 4.—*Showing manufacturing methods and certain physical properties of fire bricks*

Laboratory key letter of brand	Method of manufacture [1]	P. C. E.	Absorption in per cent of weight of dry brick		Number of quenchings required to cause failure; fire brick heated to 1,400° C. for 5 hours				Average number of quenchings in the 4-inch dip tests
			As received	After burning 5 hours at 1,400° C.	2-inch dip [2]	4-inch dip	4-inch dip	4-inch dip	
A	HM	33+	14.1	10.7	45	49	43	-------	46
B	HM	33+	10.9	9.5	38	16	6	9	10
C	DP	33+	9.6	8.1	45	29	32	-------	31
D	DP	31–32	6.7	5.3	8	34	7	10	17
E	DP	31–32	5.2	6.6	5	18	16	11	15
F	SM	31	7.0	3.0	9	11	2	2	5
G	HM, repress	32	17.6	16.1	11	8	5	-------	7
H	HM	32	16.3	17.1	12	6	3	6	5
I	HM	33	10.7	8.9	26	24	15	11	17
J	SM	28–29	8.3	3.8	6	8	6	-------	7
K	SM	32	8.2	6.8	15	10	12	-------	11
L	HM	33	8.2	6.8	32	17	18	-------	18
M	HM	33	11.7	11.4	19	14	11	-------	13
N	SM	32	5.5	4.8	4	6	5	-------	6
P	SM, repress	30	13.8	12.4	4	8	4	-------	6
Q	DP	34	7.2	6.9	>50	49	>41	-------	>45
R	HM, repress	33	13.6	12.6	3	8	8	4	7

[1] HM, SM, DP refer to handmade, stiff-mud, dry-press processes, respectively.
[2] Only one end heated at 1,400° C. for 5 hours.

4. PYROMETRIC CONE EQUIVALENTS (P. C. E.)

Table 3 gives the P. C. E. values for all the materials entering into the various brands of brick. All materials, with the exception of samples B–3 and C–2 (Pennsylvania plastic fire clays), have a P. C. E. of 30 or above.

Table 4 gives the P. C. E. values as determined on the 17 brands of fire-clay brick. The data show that with the exception of samples designated J and P, all the brands of fire-clay bricks have a P. C. E. of 31 or above.

5. THERMAL-SPALLING TEST

The results of the various spalling tests are given in Table 4. Five samples of each brand of bricks were tested for resistance to spalling in the test requiring an immersion in water of 4 inches. The test was made a second time on all brands of bricks and those brands showing great differences in results between these two tests were tested a third time. The average of the several tests gives a range, in number of cycles to cause failure of from 5 for those showing the least resistance to over 46 for those having the greatest resistance.

The number of cycles required to cause spalling in the modified spalling test, in which only one end of the brick was heated in the reheat test and a 2-inch immersion used, ranged from a minimum of 3 to a maximum of over 50.

Comparison of the results obtained in the 2-inch against 4-inch immersion tests shows a decided lack of correlation between the two tests. In several instances very little difference is noted in the number of cycles required to cause failure; in some cases the number of cycles required to cause spalling is much greater with the 2-inch immersion, and in still others the reverse is true.

6. SIZES OF GROG

Grog is burned clay, either as such or in the form of broken bricks, discarded saggers, or other cast-off refractory shapes. It is usually ground or crushed and may or may not be screened to specific sizes for use. In those plants where grog is an essential constituent of the product, it is obtained as a rule by grinding or crushing broken or discarded fire brick. The analyses made of the raw batch materials furnished by manufacturers of fire bricks showed that not all of them use grog in their product. However, those manufacturers who use considerable quantities of flint clay in their batch composition grind the flint clay to a desired size. Since the particles of flint clay do not readily slake, they probably serve a purpose similar to that of grog. A macroscopic examination of all the grog or grog substitutes remaining after washing the samples of batch material on a 200-mesh sieve resulted in classifying the various compositions as follows:

1. Largely flint clay or flint and semiflint clays with varying percentages of grog.
2. Entirely flint clay or flint and semiflint clays.
3. Large percentage of quartz with varying proportions of grog.

The appearance of 14 samples of grogs or grog substitute particles indicates that 13 were crushed and only 1 was ground.

If it is arbitrarily assumed that the material which passes a 200-mesh sieve is clay substance, then the material which did not pass the sieve, and which may be considered as grog or grog substitutes in this study, ranges from a total of 40 to 80 per cent of the raw brick batch. Table 5 tabulates the respective percentages of grog materials retained on various mesh sieves, together with the percentages of grog and clay comprising the raw brick batches.

TABLE 5.—*Sieve analysis of grog or grog substitutes used in 14 raw fire-clay brick batches*

Sample key letter	Per cent passing and retained on sieves—							
	No. 4 mesh	4 to 10	10 to 20	20 to 40	40 to 100	100 to 200	Through 200	Total grog[1]
A	2.30	17.20	21.40	11.50	11.00	4.05	32.55	67.45
B		22.00	21.20	9.40	9.80	3.40	34.20	65.80
C		9.75	33.25	16.25	15.75	5.37	19.60	80.40
D and N		1.25	18.75	22.75	20.75	6.00	30.50	69.50
E and F		.25	18.50	20.65	20.50	7.00	30.60	69.40
G	.25	11.00	11.62	7.12	13.12	5.75	51.10	48.90
H	1.12	2.64	9.50	8.25	12.75	8.74	57.00	43.00
I		9.75	28.30	12.87	11.50	3.87	33.75	66.25
J		1.50	17.75	11.28	8.62	2.25	58.60	41.40
K and L		8.75	24.25	11.00	11.00	4.87	40.10	59.90
M	.50	18.85	18.75	8.75	10.00	7.50	39.40	60.60
P		6.20	7.90	4.40	18.00	6.20	57.30	42.70
Q		1.50	19.90	39.40	14.50	13.70	11.00	89.00
R		7.50	15.38	8.50	13.25	4.63	50.70	49.30

[1] Material that did not pass a No. 200-mesh sieve was considered as grog.

7. THERMAL EXPANSION

(a) FIRE CLAYS

The thermal expansions of the 24 fire clays as well as the 5 samples of sand and quartz were determined from room temperature to 900° C. Specimens made from these materials, with the exception of 3 of the silica sands, were fired at 1,400° C. for 5 hours. The materials may be classified according to the thermal expansion behavior into five groups as follows:

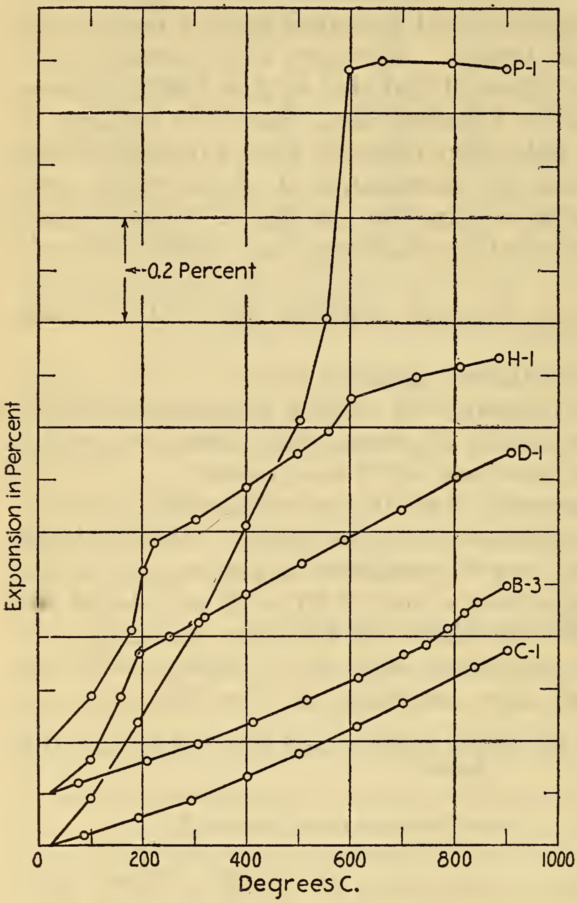

FIGURE 3.—*Curves showing linear thermal expansions characteristic of different types of fire clays*

To avoid overlapping, the curves have not all been drawn from a common origin.

1. Eleven have a high rate of expansion below 200° C. and a somewhat less and more uniform one between approximately 200° and 900° C. The curves indicate that any free silica present is either in the form of tridymite or cristobalite. Clays Nos. A–1, B–2, D–1, E–1, G–1, H–2, I–1, I–2, K–1, R–2, and T–1 belong in this group.

2. Four have a high rate of expansion below 200° C. and also between approximately 540° and 600° C. These curves show that quartz, cristobalite, and tridymite are all present in the clays. However, the expansion curves indicate the presence of only a small amount of quartz. Samples Nos. R–3, H–1, H–5, and H–6 belong in this group.

3. Three have a comparatively uniform rate of expansion throughout the range observed except for an increased expansion at approximately 575° to 600° C. These curves indicate that all silica is present in the form of free quartz. Samples Nos. H–3, H–4, and P–1 are classed in this group.

4. Three clays have a uniform expansion from room temperature to approximately 750° C. At this temperature the expansion per degree increases up to approximately 850° C., after which it gradually decreases. The clays in this group are all of the so-called plastic type, and it is quite possible that after firing for five hours at 1,400° C. sufficient glass is present to cause this change in the rate of expansion more or less typical of some glasses.[14] Samples Nos. B–2, C–2, and I–3 belong to this group.

5. Eight clays have a uniform expansion throughout the entire range of 20° to 900° C.

The materials tested, therefore, include all those having the several types of expansion due to a substantially quartz-free condition or to the presence of quartz either as such or in one of its allotropic modifications. Curves, showing the thermal expansion behavior from 20° to 900° C. of materials representative of each of the foregoing groups are given in Figure 3. The total linear expansion values per unit length from 100° to 900° C. at 100° C. intervals and also the value obtained at 550° C. are given in Table 6. The initial measurement of the specimen was made at approximately 20° C.

TABLE 6.—*Total linear thermal expansion per unit length at temperatures indicated of fire clays fired at 1,400° C. for five hours*

Laboratory key letter	Temperature° (C.)										Classed according to type of expansion in group
	100	200	300	400	500	550	600	700	800	900	
A–1	0. 000484	0. 001773	0. 002254	0. 002804	0. 003352	0. 003607	0. 003899	0. 004429	0. 004979	0. 005548	1
A–2	.000310	.000807	.001223	.001697	.002105	.002430	.002736	.003274	.003847	.004413	5
B–1	.000216	.000597	.001025	.001454	.001930	.002172	.002412	.002847	.003407	.003905	5
B–2	.000500	.001094	.001488	.001927	.002385	.002559	.002835	.003992	.003741	.004227	1
B–3	.000194	.000562	.000900	.001285	.001697	.001878	.002184	.002502	.003164	.003884	4
C–1	.000219	.000559	.000890	.001325	.001762	.001976	.002234	.002659	.003201	.003717	5
C–2	.000240	.000560	.000926	.001351	.001815	.002024	.002450	.002687	.003175	.003719	4
D–1	.000654	.002730	.003230	.003791	.004358	.004637	.004915	.005461	.006019	.006484	1
E–1	.000612	.002256	.002772	.003305	.003835	.004102	.004370	.004899	.005462	.005972	1
G–1	.000581	.002340	.002879	.003456	.004038	.004318	.004662	.005189	.005688	.006093	1
H–1	.000826	.003122	.004219	.004879	.005650	.005790	.005860	.006496	.007152	.007373	2
H–2	.000437	.001329	.001778	.002265	.002763	.003011	.003283	.003797	.004375	.004880	1
H–3 [1]	.000820	.002321	.003810	.006258	.008915	.011020	.015300	.015450	.015400	.015214	3
H–4 [1]	.000913	.002555	.004253	.006578	.009577	.010586	.015000	.015100	.015050	.014980	3
H–5	.000673	.002701	.003346	.003911	.004496	.004824	.005270	.005925	.006318	.006623	2
H–6	.000723	.004693	.006128	.006798	.007494	.007783	.008224	.008766	.009064	.009290	2
I–1	.000555	.002263	.002806	.003329	.003872	.004131	.004426	.004960	.005363	.005766	1
I–2	.000447	.001244	.001710	.002189	.002657	.002926	.003198	.003737	.004322	.004911	1
I–3	.000266	.000787	.001118	.001568	.001966	.002150	.002388	.002883	.003352	.003731	4
K–1	.000707	.002182	.002646	.003198	.003743	.004181	.004321	.004837	.005375	.005875	1
K–2	.000226	.000628	.001015	.001440	.001900	.002129	.002371	.002866	.003546	.004118	5
M–1	.000241	.000690	.001092	.001500	.001968	.002219	.002475	.002976	.003577	.004298	5
M–2	.000252	.000651	.001053	.001519	.001993	.002242	.002494	.002879	.003613	.004392	5
P–1 [1]	.000896	.002347	.003886	.006121	.008570	.010610	.014840	.014900	.014860	.014850	3
Q–1	.000235	.000673	.001062	.001552	.002022	.002271	.002540	.003089	.003917	.004530	1
R–1	.000235	.000666	.001042	.001462	.001897	.002125	.002356	.002798	.003324	.003871	5
R–2	.000735	.002048	.002587	.003125	.003700	.003970	.004348	.004808	.005365	.005308	1
R–3	.000748	.003549	.006194	.007017	.007810	.008247	.009000	.009441	.009671	.009794	2
T–1	.000676	.003571	.004273	.004872	.005490	.005794	.006122	.006717	.007166	.007569	1

[1] Observations made on the raw material which is composed largely of silica and did not sinter at 1,400° C.

[14] B. S. Sci. Paper No. 393.

(b) FIRE-CLAY BRICKS

The linear thermal expansions of the fire-clay bricks were observed from approximately 20° to 1,000° C. on a specimen cut from each of the 17 brands of bricks. Observations were made on these specimens representing bricks (*a*) as received from the manufacturer, (*b*) after refiring for five hours at 1,400° C., (*c*) after the same specimen had been fired again at 1,500° C. for five hours, and (*d*) an additional firing for three hours at 1,600° C.

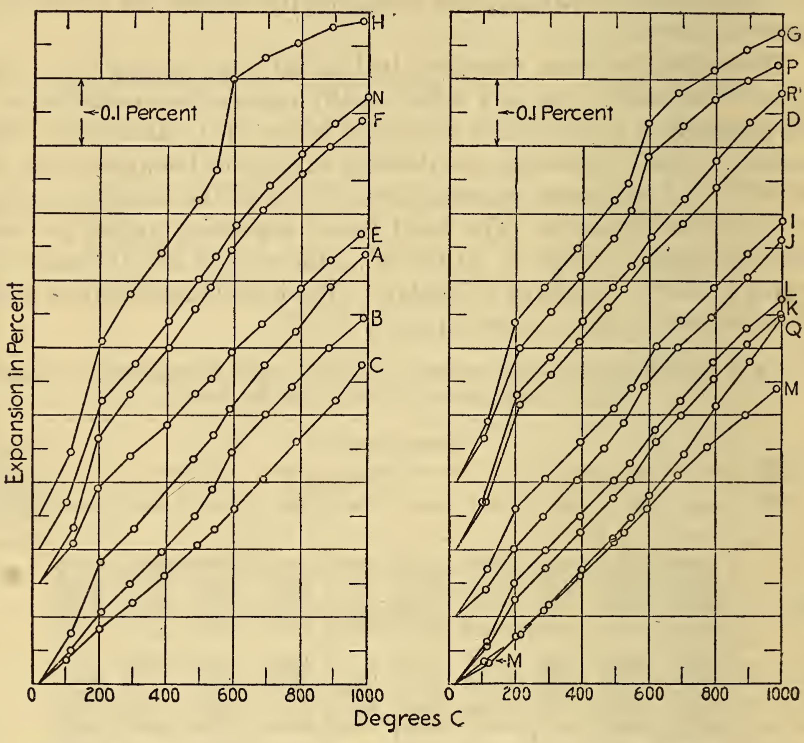

FIGURE 4.—*Curves showing linear thermal expansions of 17 brands of fire-clay brick as "received" from the manufacturer*

To avoid overlapping, the curves have not all been drawn from a common origin.

The bricks may be classified into four groups according to the type of expansion observed on the specimen as received from the manufacturer.

1. Three brands, C, M, and Q, were found to have a comparatively uniform rate of expansion.

2. Three brands, D, N, and R, had a high rate of expansion below 200° C. and a uniform rate from approximately 200° to 1,000° C.

3. One brand only, J, showed a high expansion between 550 and 600° C., indicating an inversion of alpha-to-beta quartz.

4. The other 10 brands show an increased expansion both below 200° C. and also between approximately 550° and 600° C., although the

alpha-to-beta quartz inversion is comparatively slight in the case of seven brands in this group.

Thermal expansion curves, plotted from observations on the 17 brands of fire-clay bricks as received from the manufacturer, are shown in Figure 4.

Check determinations were made on 6 specimens of fire clay and 11 of fire-clay bricks. The greatest variation in the data obtained on the same body was less than 2½ per cent.

(c) EFFECT OF TEMPERATURE OF FIRING ON THERMAL EXPANSION

The changes in the physical composition of the bricks brought about by reheating them at 1,400°, 1,500°, and 1,600° C. are well illustrated by the data obtained on the linear thermal expansion.[15]

In Table 7 are given data on the expansion behavior of the bricks "as received" and after reheating in the laboratory kiln at 1,400°, 1,500°, and 1,600° C. The total linear expansions per unit length between 100° and 200° C., 500° and 600° C., and 20° to 1,000° C., together with the coefficient of expansion between the latter temperatures are tabulated. The data shown for these temperature ranges illustrate the effect on the thermal expansion of the refractory produced by progressively increased firing temperatures. With few exceptions the expansion decreases as the temperature of firing is increased. These data also show that it would be very misleading to consider an average coefficient of expansion for a single range as large as from 20° to 1,000° C. as representative of the expansion behavior of the material, since it does not indicate whether the rate throughout this range is uniform or highly irregular. A typical example of this is illustrated by the data for brand H. The variation in total expansion from 20° to 1,000° C. is comparatively small with change of firing temperatures, although the change in this property is quite large between 100° and 200° C. and especially so between 500° and 600° C. In addition, the expansion increased between 100° and 200° C. and decreased between 500° and 600° C.

TABLE 7.—*Expansion in per cent and coefficient of expansion of fire brick*

Brand	Temperature of firing	Range of temperature (° C.)			Coefficient [1] expansion of 20 to 1,000° C.
		100 to 200	500 to 600	20 to 1,000	
A	(2)	0.116	0.069	0.635	6.5
	(3)	.053	.053	.473	4.8
	(4)	.048	.050	.485	5.0
	(5)	.046	.046	.440	4.5
B	(2)	.064	.089	.541	5.5
	(3)	.038	.047	.421	4.3
	(4)	.043	.046	.419	4.3
	(5)	.047	.059	.483	4.9

Footnotes at end of table.

[15] Thermal expansion data similar to those obtained in this investigation were found by Miehr, Kratzert, and Immke, described in their paper, Influence of Firing on the Chemical and Physical Properties of Refractory Clays, Tonindustrie Zeitung, 52 (16); 1928.

TABLE 7.—*Expansion in per cent and coefficient of expansion of fire brick*—Con.

Brand	Temperature of firing	Range of temperature (° C.)			Coefficient of expansion [1] 20 to 1,000° C.
		100 to 200	500 to 600	20 to 1,000	
C	(2)	0.059	0.058	0.462	4.7
	(3)	.035	.046	.410	4.2
	(4)	.035	.046	.412	4.2
	(5)	.038	.045	.402	4.1
D	(2)	.141	.051	.603	6.4
	(3)	.091	.045	.497	5.1
	(4)	.033	.038	.390	4.0
	(5)	.028	.041	.358	3.7
E	(2)	.096	.061	.530	5.4
	(3)	.079	.046	.486	5.0
	(4)	.035	.040	.365	3.7
	(5)	.042	.052	.398	4.1
F	(2)	.150	.078	.698	7.1
	(3)	.093	.043	.509	5.2
	(4)	.025	.044	.355	3.6
	(5)	.028	.039	.347	3.5
G	(2)	.153	.121	.680	6.9
	(3)	.153	.111	.642	6.5
	(4)	.166	.055	.716	7.3
	(5)	.045	.044	.424	4.3
H	(2)	.177	.218	.770	7.8
	(3)	.190	.175	.739	7.5
	(4)	.205	.068	.730	7.5
	(5)	.225	.047	.740	7.6
I	(2)	.098	.077	.590	6.1
	(3)	.047	.055	.492	5.0
	(4)	.044	.051	.442	4.5
	(5)	.047	.050	.421	4.3
J	(2)	.062	.085	.569	5.7
	(3)	.036	.041	.439	4.4
	(4)	.035	.042	.399	4.5
	(5)	.031	.051	.466	4.7
K	(2)	.079	.067	.546	5.6
	(2)	.055	.050	.412	4.2
	(4)	.038	.051	.432	4.5
	(5)	.038	.058	.446	4.5
L	(2)	.096	.065	.571	5.9
	(3)	.036	.045	[6] .341	[6] 4.0
	(4)	.038	.042	.421	4.3
	(5)	.038	.050	.441	4.5
M	(2)	.038	.052	.472	4.8
	(3)	.037	.051	.433	4.4
	(4)	.039	.045	.437	4.5
	(5)	.039	.047	.438	4.3
N	(2)	.155	.074	.673	6.9
	(3)	.110	.054	.574	5.9
	(4)	.037	.046	[6] .384	[6] 4.4
	(5)	.037	.043	.450	4.6
P	(2)	.127	.117	.632	6.5
	(3)	.098	.101	.546	5.6
	(4)	.066	.058	.542	5.5
	(5)	.054	.042	.487	5.0
Q	(2)	.043	.061	.544	5.5
	(3)	.033	.055	.500	5.1
	(4)	.037	.054	.493	5.0
	(5)	.035	.056	.520	5.3
R	(2)	.151	.068	.678	6.9
	(3)	.105	.062	.612	6.3
	(4)	.040	.050	.405	4.1
	(5)	.035	.045	.447	4.6

[1] To be multiplied by 10^{-6}.
[2] Data obtained on bricks as received from the manufacturer.
[3] Data obtained after firing 5 hours in laboratory kiln at 1,400° C.
[4] Data obtained after firing 5 hours in laboratory kiln at 1,500° C.
[5] Data obtained after firing 3 hours in laboratory kiln at 1,600° C.
[6] Data obtained at 900° C.

The change in total expansion because of progressive heat treatment ranges from a low of approximately 5 per cent to a high of 50 per cent.

Those brands of bricks showing an excess of alumina in their rational composition [16] or only a small percentage of free silica as computed from the chemical analyses, showed the least change in expansion after the heating treatment. Very little change was apparent in the expansion data of these brands after the firings at either 1,400°, 1,500°, or 1,600° C. The greatest change in this property appears to have been in those brands having uncombined silica exceeding 10 per cent. Typical curves showing the change in thermal expansion due to progressive heat treatment of the various types of bricks are shown in Figures 5 and 6. The curves shown in these

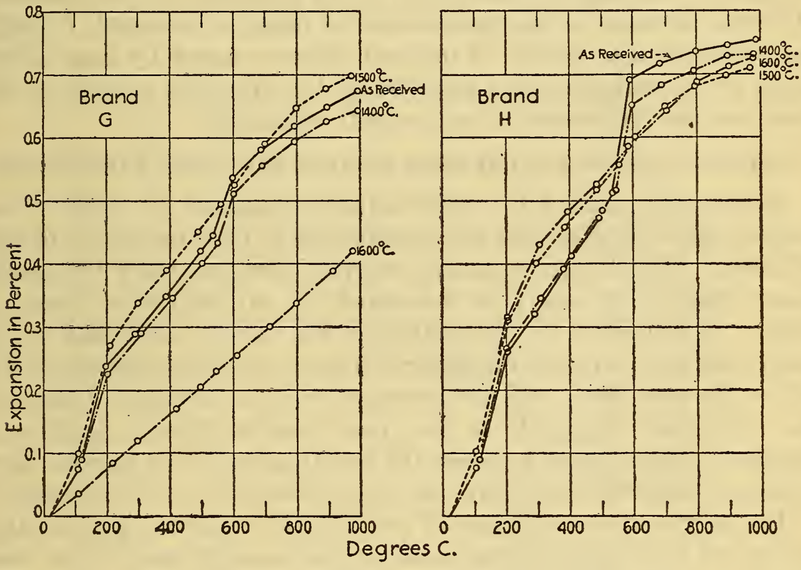

Figure 5.—*Effect on the thermal expansions of highly siliceous fire brick caused by progressively increasing firing temperatures*

figures illustrate the rates of expansion as well as the total linear thermal expansion from approximately 20° to 1,000° C. that are typical of the various brands of fire-clay bricks manufactured in this country. The data, from which the points on these curves were computed, were determined on bricks of widely different expansion behavior, such as those of brand H, having a high as well as irregular rate of expansion below 600° C.; to those of type Q, having a moderate but uniform rate throughout the range observed. These data indicate that, in those bricks showing high rates of expansion due to inversions both of cristobalite and quartz, there is first, solution of the latter form of

[16] B. S. Tech. Paper No. 279, p. 126.

silica and then of the former. The linear thermal expansion curves of 14 of the 17 brands of fire-clay bricks when tested "as received" were irregular. With but one exception (brand H) after heating these bricks at either 1,400°, 1,500°, or 1,600° C. the expansion became uniform and lower. In other words, it appears that if heated sufficiently, all fire-clay bricks of the quality included in this study will have practically the same type and rate of thermal expansion regardless of the nature of the materials used originally in their manufacture. Brand H, which is an exception, is a highly siliceous brick. A petrographic examination of fire-clay bricks of brands G and H, after the final reheating at 1,600° C., showed the materials to consist of only well-developed crystals of mullite embedded in glass.

Since these data show that the thermal expansions of the majority of bricks decrease as the temperature of firing is increased, it might be concluded that finally all internal stresses caused by large differences in thermal-expansion behavior of the fire clays making up the brick are greatly reduced if not entirely eliminated.

(d) FIRE-CLAY BRICKS AND FIRE CLAYS ENTERING INTO THEIR MANUFACTURE

As previously stated, the manufacturers furnished the names of the various clays entering into the manufacture of their respective brands of brick. The thermal-expansion curves, therefore, show the results from blending the clays as illustrated by any particular brand of brick. Inasmuch as the proportions of the various clays used in any particular batch are not the same, it follows that the expansion curve of the fire-clay brick will not necessarily be the average of those of the individual clays. It is also quite possible that a reaction or physical change occurs between the constituents of the various clays during heating which may have an appreciable effect on the expansion.[17]

The curves shown in Figures 7 and 8 in all instances represent data computed from observations made on the material after it had been fired at 1,400° C. for five hours. The thermal expansions of each of the three materials (broken lines) entering into the composition of fire-clay brick brand R as well as that of the brick (full line) are shown in Figure 7. These curves illustrate the large differences which may occur in expansion behavior of the individual materials entering into one composition and the resultant effect on the final product. In this instance the expansion of the brick is approximately the computed average of those of the materials entering into its composition based on the percentage of each material present. It would be logical to assume that such large differences in the thermal expansions between materials constituting a refractory would cause interstructural stresses greatly affecting the life of the product.

[17] Willi M. Cohn discusses the behavior of minerals and ceramic bodies on heating in his paper entitled "Some Factors Influencing the Thermal Properties of Minerals and Products of the Ceramic Industry," J. Am. Ceram. Soc., **11** (5); 1928.

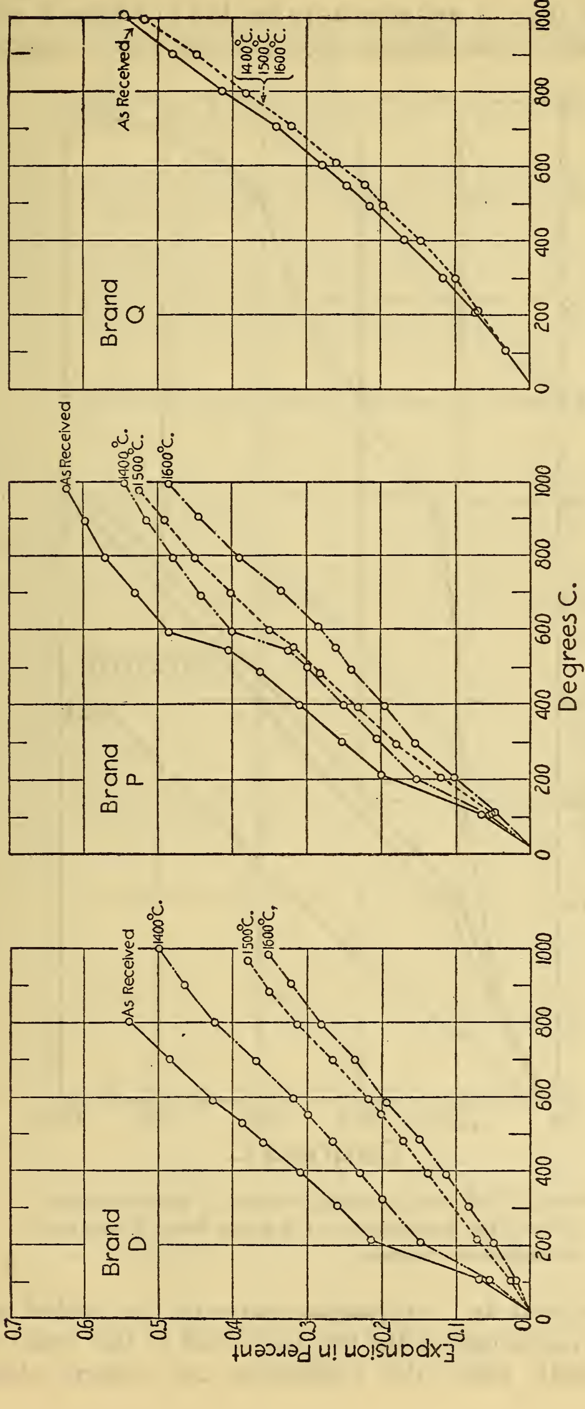

FIGURE 6.—*Effect on the thermal expansions of fire-clay brick, not of the highly siliceous type, caused by progressively increasing firing temperatures*

In contrast to the expansion curves for materials entering into fire-clay brick R (fig. 7) are shown, to the left in Figure 8, expansion curves obtained on the different clays entering into the manufacture

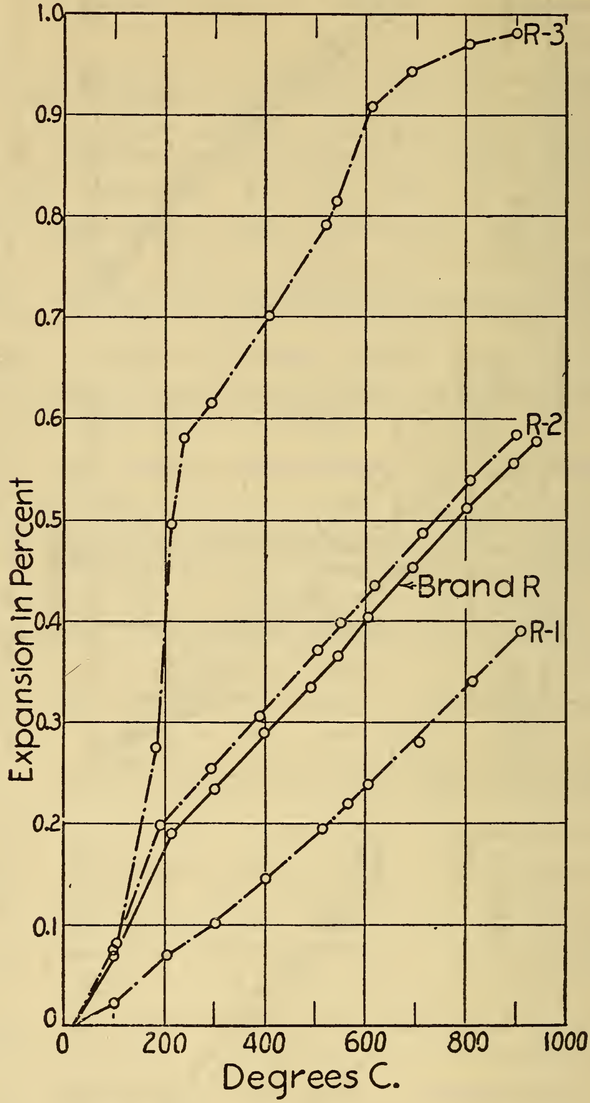

FIGURE 7.—*Thermal expansion curves of materials entering into the manufacture of fire-clay brick R and that of the finished product*

of brick C as well as e expansion curve of the finished product. The thermal expansions of the two clays used in this brand of brick are very nearly alike; the expansions are uniform throughout

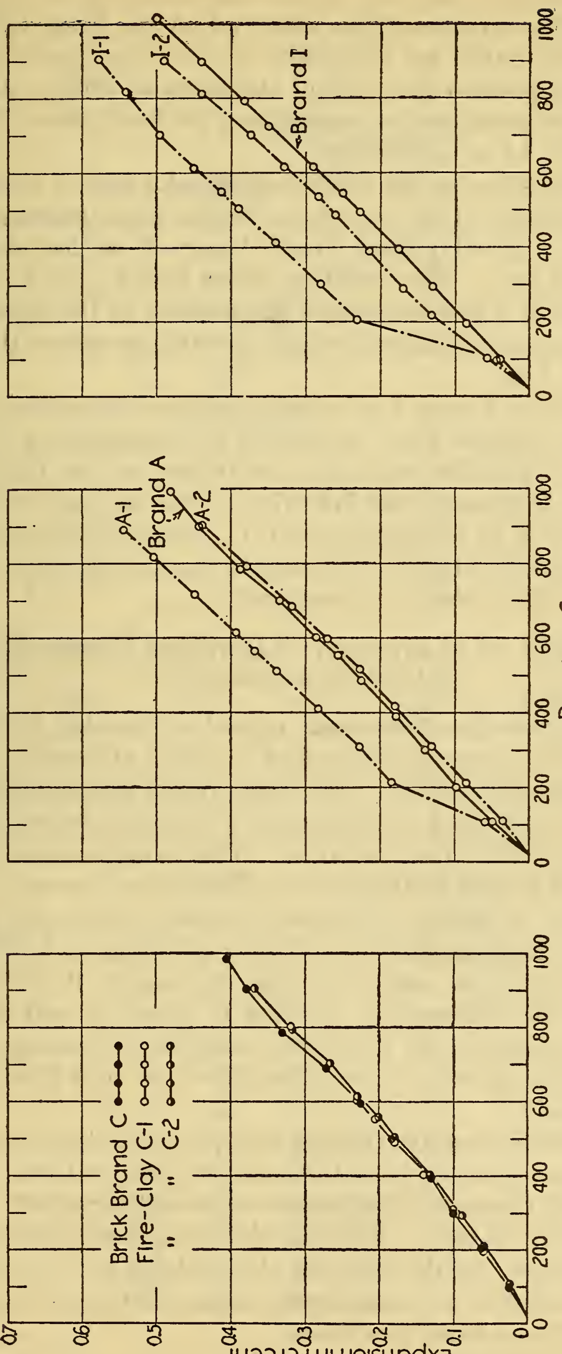

FIGURE 8.—*Showing the expansion curves of three brands of brick and the clays used in their manufacture*

the range observed, and the total expansions are low for fire-clay materials. The expansion data observed on the brick (shown as a full line in the graph) are practically the same as those for the two clays. The expansion behavior of the clays as well as that of the brick might be considered as approaching the ideal, since the internal stresses should be at a minimum.

The curves shown in the center section of Figure 8 illustrate the expansion behavior of the two clays (broken lines) entering into the manufacture of fire-clay brick brand A as well as that observed on the brick (full line). The inflection, below 200° C., in the expansion curve for clay A–1 has completely disappeared in the finished product, the expansion behavior of which closely approaches that of the bonding clay A–2.

On the right in Figure 8 are shown the linear expansion curves of the two clays (broken lines) blended in the manufacture of fire-clay brick brand I, together with that determined on the final product. The expansion curve for the fire brick in this case not only fails to show any sign of an inflection at 200° C., which is quite pronounced in the curve for fire clay I–1, but also is appreciably lower than that of either clay from which it is prepared.

8. MODULUS OF ELASTICITY, TRANSVERSE STRENGTH, AND MAXIMUM ELONGATION

Figure 9 shows the deflections, typical of fire-clay bricks, corresponding to the various loads applied to bricks of brand C and plotted to a convenient scale. The stress (load) strain (deformation) curves were determined on specimens 1 inch in cross section and 9 inches long, cut from the fire bricks. They were placed across an 8-inch span and loaded at the center. The curves shown in Figure 9 were obtained on bricks, all tested at approximately 20° C., (*a*) as received from the manufacturer, (*b*) after reheating at 1,400° C., and (*c*) after reheating at 1,500° C. The decrease in flexibility of the material, as the temperature of firing is raised, is well illustrated. The data obtained at 20° C. on the modulus of elasticity of the 17 brands of bricks tested after receiving the three heat treatments are given in Table 8.

The transverse strengths (moduli of rupture) of the various brands of bricks were computed from the loads required to break the specimens on which the load-deflection curves were determined. The values are shown in Table 8. The data show that the modulus of elasticity had increased greatly and that the modulus of rupture had also increased, but not to the same degree as the modulus of elasticity, as the temperature of firing was raised.

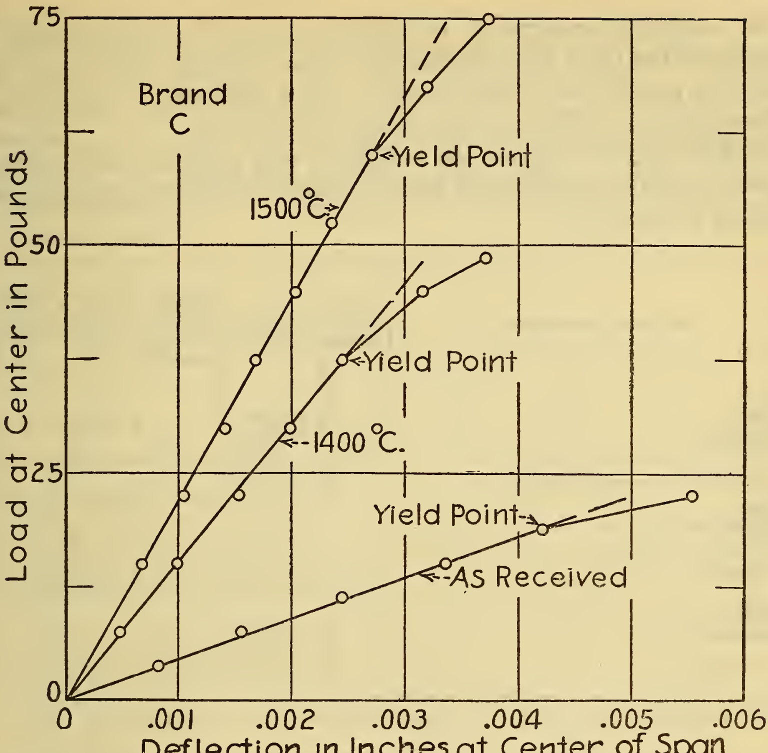

FIGURE 9.—*Curve showing the typical stress (load), strain (deformation), relationship of fire-clay bricks as the temperature of firing is increased*

TABLE 8.—*Properties of commercial fire-clay brick tested at 20° C.*

Laboratory key letter of brand	As received from manufacturer			After reheating at 1,400° C. for 5 hours			After reheating at 1,500° C. for 5 hours		
	Modulus of—		Maximum elongation (R/E)[2]	Modulus of—		Maximum elongation (R/E)[2]	Modulus of—		Maximum elongation (R/E)[2]
	Elasticity[1]	Rupture		Elasticity[1]	Rupture		Elasticity[1]	Rupture	
	Lbs./in.²	*Lbs./in.²*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*
A	631	270	0.04	920	525	0.06	2,430	875	0.04
B	1,434	640	.04	1,350	380	.03	2,670	560	.02
C	510	265	.05	1,890	520	.03	2,450	805	.03
D	974	620	.06	1,520	830	.06	4,040	1,485	.04
E	640	1,030	.16	2,670	1,415	.05	8,380	2,000	.02
F	2,800	1,560	.06	3,170	1,775	.06	9,490	1,575	.02
G	920	760	.08	1,070	625	.06	2,605	980	.04
H	250	235	.09	353	335	.09	------	------	------
I	990	590	.06	2,300	885	.04	3,665	1,345	.04
J	2,580	1,355	.05	6,400	1,470	.02	([3])	([3])	([3])
K	2,170	1,195	.05	2,700	925	.03	4,995	1,230	.02
L	2,145	580	.03	3,145	910	.03	4,440	1,485	.03
M	2,110	720	.03	4,500	1,210	.03	6,920	1,295	.02
N	3,345	1,430	.04	3,950	1,415	.04	3,635	1,420	.04
P	1,665	950	.06	1,950	955	.05	2,930	1,230	.04
Q	2,025	915	.04	2,700	1,190	.04	5,340	1,520	.03
R	3,350	1,225	.04	3,720	1,285	.03	4,630	1,495	.03

[1] To be multiplied by 10^3.

[2] Maximum elongation of extreme fiber at point of rupture of specimens $= \frac{\text{Modulus of rupture}}{\text{Modulus of elasticity}} = R/E$.

[3] Bloated.

73113°—29——7

The maximum elongation at rupture, for each of the brands of bricks after the three heat treatments, is also given in Table 8. The maximum elongation of the material had a tendency to decrease as the temperature of firing of the material was raised.

The following table gives the maximum and minimum and average values of certain properties of bricks made by different processes and reheated at 1,400° C.:

Method of manufacture	Number of brands	Modulus of elasticity	Absorption in per cent of dry weight	Failed in quenching test after	Linear thermal expansion between 100° to 200° C.
Handmade:		*Lbs./in.²*		*Cycles*	*Per cent*
Maximum	--------	4, 500, 000	17. 1	46	0. 190
Minimum	--------	353, 000	6. 8	5	. 036
Average	8	2, 139, 000	11. 6	15	. 082
Dry press:					
Maximum	--------	3, 140, 000	8. 1	45	. 079
Minimum	--------	1, 520, 000	5. 3	15	. 033
Average	4	2, 305, 000	6. 7	>27	. 059
Stiff mud:					
Maximum	--------	6, 400, 000	12. 4	11	. 110
Minimum	--------	2, 050, 000	3. 0	5	. 055
Average	5	3, 654, 000	[1] 6. 1	7	. 078

[1] Omitting brand P (12.4 per cent) from this group causes this value to drop to 4.6 per cent.

The bricks manufactured by the stiff-mud process have the highest average modulus of elasticity and the lowest average absorption. These qualities, together with the high rate of thermal expansion between 100° and 200° C. and the possibility of laminated structure, may be the causes of the low resistance to spalling of this type of bricks.

The low rate of thermal expansion between 100° to 200° C. indicated by the dry-press brick is probably the explanation for the high resistance to spalling shown.

9. BRICKS TESTED AT SEVERAL TEMPERATURES

The modulus of elasticity, transverse strength, and maximum elongation of each of the 17 brands of bricks after reheating at 1,400° C. for five hours, were determined at 20°, 550°, and 1,000° C. The results of these tests (given in Table 9), with but two exceptions, show that both the modulus of elasticity and transverse strength were greater at 550° C. than at 20° C. The percentage increase in modulus of elasticity attending an increase in temperature from 20° to 550° C. is greater than the corresponding increase in transverse strength. The effect of higher temperatures on the modulus of elasticity is illustrated in Figure 10. The average modulus of elasticity determined at 550° C. as compared with that at 20° C. of the bricks made by the stiff-mud process had increased twice as much as that of the bricks made by the handmade process. The increase in the modulus of elasticity of the bricks, made by the dry-press method, was intermediate between the increases shown by the bricks made by the other two methods. At 1,000° C. the modulus of rupture had increased moderately and the modulus of elasticity had decreased greatly.

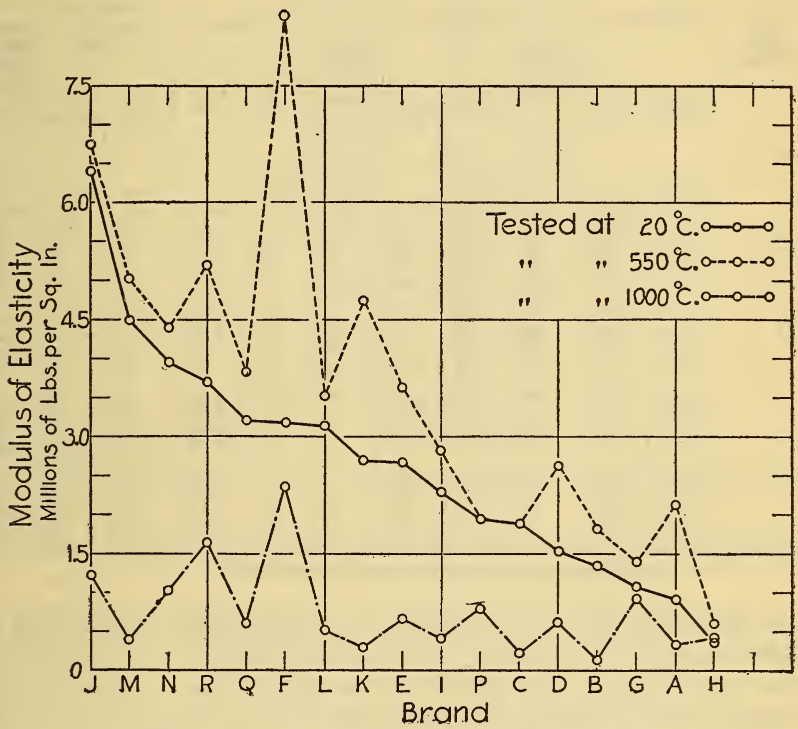

FIGURE 10.—*Effect of temperature on the modulus of elasticity of 17 brands of fire-clay brick*

At 550° C. the maximum elongation of the extreme fiber had decreased when compared with that obtained at 20° C. The formula for computing the outer fiber deformation is based on a linear relationship of the load-deflection curve. At 1,000° C. this relationship was found to be not linear; therefore, the secant modulus of elasticity was computed and this value substituted in the formula for determining maximum strain values at 1,000° C.[18] Table 9 shows the maximum elongation values as computed, using either the tangent or secant

[18] Maximum strain values at 1,000° C. of clay bodies are discussed in detail in the Fourth Progress Report of the Sagger Investigation, J. Am. Ceram. Soc., 10 (12), pp. 995–1004; 1927.

modulus. It is believed that the values obtained using the secant modulus represent more nearly the true deformation of the clays at 1,000° C.

TABLE 9.—*Properties of commercial brands of fire brick reheated at 1,400° C. for five hours*

Key letter of brand	Tested at 20° C.			Tested at 550° C.			Tested at 1,000° C.				
	Modulus of—		Maximum elongation	Modulus of—		Maximum elongation	Modulus of—		Maximum elongation using		Plastic flow (inches) after 1 hour stress
	Elasticity	Rupture		Elasticity	Rupture		Elasticity	Rupture	Tangent modulus	Secant modulus	
	1,000 lbs./in.²	*Lbs./in.²*	*Per cent*	*1,000 lbs./in.²*	*Lbs./in.²*	*Per cent*	*1,000 lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*	*60 lbs./in.²*
A	920	525	0.06	2,220	710	0.03	333	730	0.22	0.51	0.0008
B	1,350	380	.03	1,820	770	.04	147	640	.43	1.50	.0015
C	1,890	520	.03	1,890	550	.03	227	560	.25	.44	.0008
D	1,520	830	.06	2,660	1,275	.05	626	1,015	.16	.45	[1] .0009
E	2,670	1,415	.05	3,640	1,610	.04	674	2,010	.30	.40	.0012
F	3,170	1,775	.06	8,400	2,520	.03	2,372	3,320	.14	1.65	.0002
G	1,070	625	.06	1,400	850	.06	894	1,275	.14	.20	.0005
H	353	335	.09	610	450	.07	426	695	.16	.29	.0005
I	2,300	885	.04	2,840	1,140	.04	424	810	.19	.32	[1] .0008
J	6,400	1,470	.02	6,750	2,100	.03	1,217	2,620	.22	.69	.0047
K	2,700	925	.03	4,760	1,355	.03	331	2,750	.83	.90	.0042
L	3,145	995	.03	3,520	1,390	.04	531	1,390	.26	.47	.0007
M	4,500	1,210	.03	5,025	1,550	.04	410	2,320	.57		.0006
N	3,950	1,415	.04	4,400	1,650	.04	1,032	1,525	.12	.16	.0001
P	1,950	955	.05	1,950	980	.05	808	1,375	.17	.27	.0004
Q	3,210	1,195	.04	3,830	1,200	.03	614	1,135	.18	.60	.0002
R	3,720	1,285	.03	5,200	1,620	.03	1,649	1,550	.09	.17	.0016

[1] These values were obtained using a stress of approximately 120 lbs./in.².

A number of the test specimens of fire-clay bricks were found to be defective, as evidenced by the rupture occurring at a point other than approximately the middle of the 8-inch span. In such cases the required data were determined on a second specimen. Check determinations of moduli of elasticity and rupture were made on 10 specimens and the results procured on the same body varied in the majority of cases less than 10 per cent. The two values obtained for each material are given in Table 10.

TABLE 10.—*Determinations and checks of moduli of elasticity and rupture obtained on commercial and laboratory prepared fire-clay brick after firing five hours at 1,400° C.*

Specimen	Modulus of elasticity	Modulus of rupture	Results obtained at—
	Lbs./in.²	*Lbs./in.²*	
H [1]	365,000	310	Room temperature.
	340,000	360	Do.
L [1]	2,900,000	950	Do.
	3,390,000	1,040	Do.
P [1]	1,849,000	920	Do.
	2,050,000	990	Do.
Q [1]	3,140,000	1,125	Do.
	3,280,000	1,260	Do.
Q—(SM)	3,400,000	950	Do.
	3,480,000	1,000	Do.
C—(DP)	2,250,000	865	550° C.
	1,900,000	790	Do.
E—(SM)	7,230,000	2,530	Do.
	8,120,000	(2)	Do.
1—(HM)	4,175,000	1,445	Do.
	4,010,000	1,400	Do.
L—(DP)	2,530,000	995	Do.
	2,890,000	825	Do.
Q—(SM)	2,680,000	830	Do.
	2,720,000	855	Do.

[1] Commercially prepared firebricks.
[2] No data.

NOTE.—(SM), (DP), and (HM) refer to stiff-mud, dry-press, and handmade methods of preparation of bricks made in the laboratory.

10. SOME REASONS FOR VARIATION IN RESISTANCE TO THERMAL SHOCK OF THE SAME BRAND OF BRICKS

The individual bricks in each set on which the thermal spalling test was made varied considerably in the number of quenchings required to produce failure. Two bricks which had been subjected to this test and which showed a great difference in spalling resistance were, therefore, selected from one set of each of two different brands of bricks. In addition, two bricks showing approximately the same resistance were selected from one set of a third brand. The modulus of elasticity, transverse strength, and thermal expansion of specimens cut from each of these bricks were determined. Curves showing the thermal expansion behavior are given in Figure 11. The curves plotted in the center section and in the section to the left of the center were obtained on bricks showing a large difference in spalling resistance. The lower curve in each case represents the expansion behavior of the bricks from one set showing the greater resistance to spalling. The expansion behavior of bricks showing approximately the same resistance to spalling is illustrated by the curve in the section to the

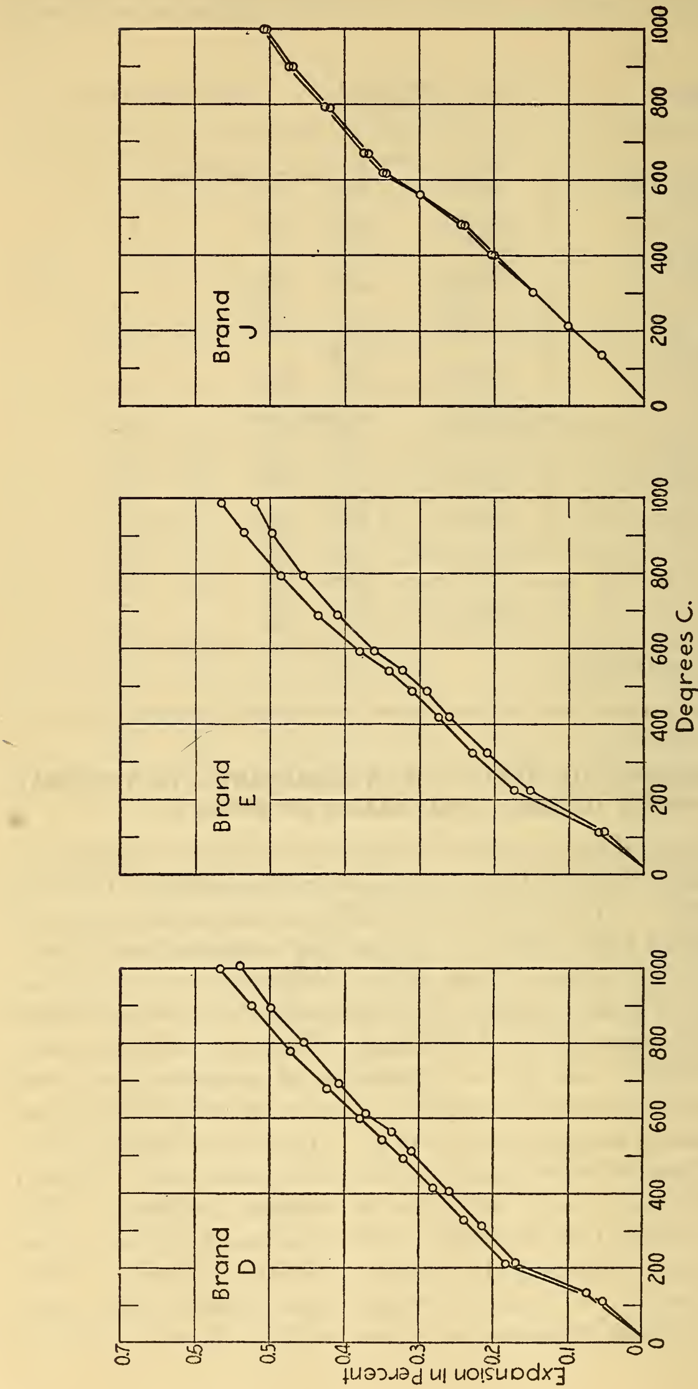

FIGURE 11.—*Curves showing expansion behavior of two bricks each of brands D, E, and J*

Individual bricks in one test of brands D and E showed great differences in resistance to spalling whereas the two of brand J showed practically the same resistance.

right of the center. The rate of expansion of the two bricks is practically identical. Results of the other tests made on these specimens are as follows:

Brand letter	Number of quenchings to cause spalling	Modulus of elasticity	Modulus of rupture	Total thermal expansion at 1,000° C.
		Lbs./in.²	*Lbs./in.²*	*Per cent*
D	3	3, 360, 000	420	0. 567
D	45	2, 318, 000	300	. 540
E	5	1, 530, 000	1, 310	. 568
E	15	836, 000	775	. 517
J	8	904, 000	420	. 508
J	9	976, 000	710	. 504

These data show that the large variations in spalling behavior of bricks of the same brand are not altogether due to the method of testing for resistance to spalling, but may be caused by large differences in the properties of the individual bricks. It will be noted that very little difference is shown in the modulus of elasticity and thermal expansion of the two bricks of brand J, showing practically the same resistance to spalling, whereas bricks of brands D and E show large differences in these properties and also show great differences in resistance to spalling. The bricks of both brands D and E having low resistance to thermal shock have the higher moduli of elasticity and higher thermal expansion.

The results obtained in these tests are not comparable with those tabulated in Table 8, since the tests were made on specimens using a 6-inch instead of an 8-inch span. The results show that the modulus of rupture decreases greatly after a brick has been subjected to the thermal shock test, as may be seen from a comparison of the results in the foregoing tabulation with those in Table 8. Such a relation has also been found by Parmelee and Westman.[19]

11. RELATION BETWEEN RESISTANCE TO THERMAL SPALLING AND MODULUS OF ELASTICITY

If the various brands of bricks are grouped into two classes, according to whether they withstood a greater or lesser mumber of quenchings than 15 in the spalling test and the averages of these groups are compared with the average moduli of elasticity of the same groups, the following results are obtained:

Number of brands[a]	Average number of quenchings to cause spalling	Average modulus of elasticity
		Lbs./in.²
6	27	2, 190, 000
9	9	3, 505, 000

[a] Brands G and H are omitted from these averages because of their highly siliceous nature, and their early failure in the water spalling test is in all probability due primarily to high thermal dilatation.

[19] The Effect of Thermal Shock on the Transverse Strength of Fire-Clay Brick, J. Am. Ceram. Soc., 11 (12); 1928.

These averages indicate that the resistance of bricks to spalling increases as the modulus of elasticity decreases.

12. RELATION BETWEEN RESISTANCE TO SPALLING AND THERMAL EXPANSION

The brands of bricks were grouped into two classes, according to whether the total expansion, per unit length, between 100° and 200° C. after firing at 1,400° C., as given in Table 4, was greater or less than 0.06 per cent. The averages of these groups are compared with the average number of quenchings the groups withstood before failure in the spalling test. The results are as follows:

Number of brands	Average thermal expansion	Average number of quenchings to cause spalling
	Per cent	
9	0.039	22
8	.102	8

These averages indicate that high thermal expansion is conducive to early failure in the thermal spalling test.

13. RELATION OF MODULUS OF ELASTICITY, EXPANSION, TRANSVERSE STRENGTH, PERCENTAGE OF GROG TO RESISTANCE TO SPALLING

Some data have been presented by Norton [20] and Booze [21] indicating a possible relation between resistance of fire brick to spalling and the three factors (1) modulus of elasticity, (2) thermal expansion, and (3) rate of temperature change or diffusivity. An empirical relation, combining the three factors, (1) modulus of elasticity, (2) expansion, and (3) transverse strength, expressing the relative resistance R of saggers to failure due to thermal shock is given in the Third Progress Report of the Investigation of Sagger Clays.[22] It has been shown in the present report that a relation apparently exists between resistance of brick to spalling and elasticity and thermal expansion. A study of the data also indicates that bricks having an absorption below 5 and above 12 per cent show less resistance to spalling than do those having absorptions within these limits. The formula with which the resistance factor R may be computed has been changed to include a value for total grog present in the green brick batch. It is

[20] J. Am. Ceram. Soc., 8 (1); 1925.
[21] J. Am. Ceram. Soc., 8 (6); 1925.
[22] J. Am. Ceram. Soc., 10 (7), pp. 524-534; 1927.

believed that this value gives some indication of the relative thermal conductivity of the materials. The formula at present reads as follows:

$$R = \frac{M.\ G}{E.\ e}$$

where

R = factor indicating relative resistance of brick to spalling.
M = modulus of rupture.
G = grog expressed in parts of green batch materials (in per cent divided by 100).
E = modulus of elasticity.
e = coefficient of expansion for the temperature range 20° to 250° C.

The computed resistance values R are given in Table 11, together with the number of quenchings required to cause failure. Figure 12

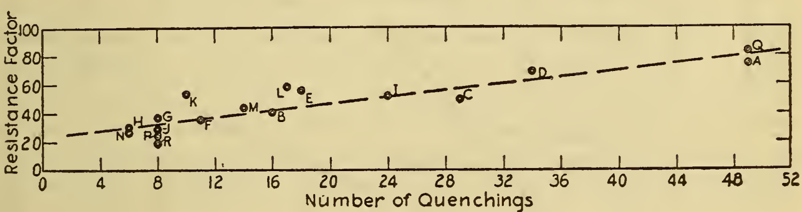

FIGURE 12.—*The computed resistance (R) of bricks to spalling plotted against the number of quenchings required to cause failure*

shows that the factor R is roughly proportional to the number of quenchings showing that the quantity $\frac{M.\ G}{E.\ e}$ is a fairly good indication of the resistance of a brick to spalling.

TABLE 11.—*Showing computed resistance factor and number of quenchings required to cause failure of fire bricks*

Laboratory key letter of brand	Resistance factor R	Number of quenchings to cause failure	Laboratory key letter of brand	Resistance factor R	Number of quenchings to cause failure
A	74	49	J	29	8
B	41	16	K	54	10
C	50	29	L	59	17
D	70	34	M	44	14
E	57	18	N	27	6
F	36	11	P	25	8
G	38	8	Q	83	49
H	31	6	R	19	8
I	52	24			

14. PLASTIC FLOW

If the form of a body is found to be permanently altered when the stress exceeds a certain value, the body is said to be plastic for stresses in excess of this value.[23] Typical load-deflection curves as obtained at 1,000° C. on a specimen cut from fire-clay brick brand K reheated at 1,400° C. are shown in Figure 13. The upper curve shows the plastic flow of the material under various loads, the lower curve the total deformation under these same loads, and the middle curve the elastic properties. The elastic recovery of the material was considered as the difference between the total deflection caused by the

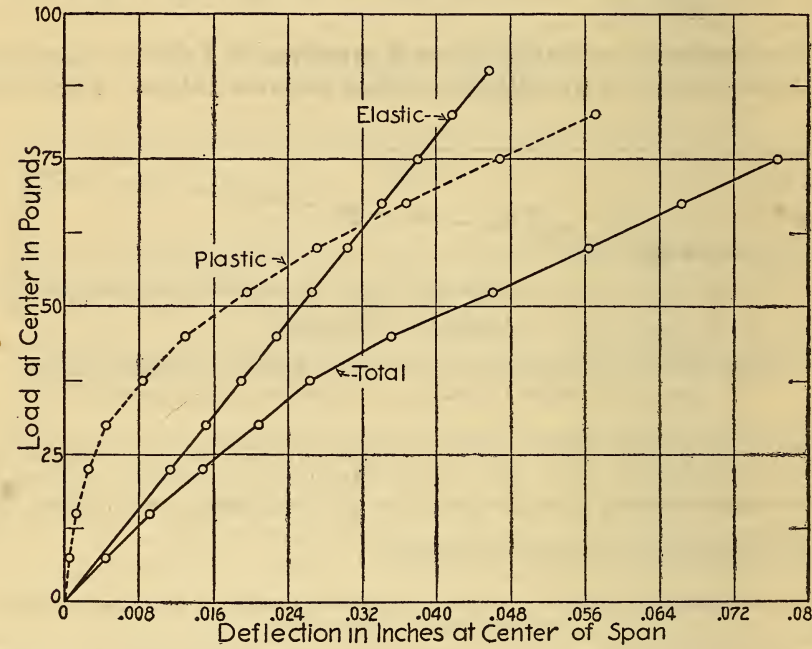

FIGURE 13.—*Load-deflection curves of fire-clay brick, brand K, at 1,000° C.*

The total deflection, plastic flow or set, and the elastic properties obtained with various stresses are shown.

load and the "set" of the material on removal of this load. The plastic flow of the various brands of bricks is given in Table 9. The values given represent the flow of the material at a temperature of 1,000° C. at the end of one hour using a load of approximately 60 lbs./in.^{2}, a specimen with a cross section of approximately 1 inch, and an 8-inch span. The smallest deflection, 0.0001 inch, is shown by brand N and the largest deflection, 0.0047 inch, by brand J. It is possible that certain of these values not only include the deflection

[23] B. S. Sci. Paper No. 278.

associated with softening of the matrix, but also may represent a partial breaking down of the physical structure. However, no breaking down in structure was evident in tests made with equivalent loads at room temperature.

V. FIRE-CLAY BRICKS PREPARED IN THE LABORATORY FROM BATCH MATERIALS FURNISHED BY MANUFACTURERS

1. GENERAL

Bricks have been made in the laboratory by each of the three methods most commonly employed in the manufacture of fire-clay bricks; namely, dry-press, stiff-mud-extruded (end cut), and handmade from prepared batch materials furnished by 14 manufacturers of fire-clay refractories.[24] These bricks were fired at 1,400° C. for five hours. In preparing these bricks it was realized that (*a*) it would be impossible to duplicate firing conditions of industrial kilns in the laboratory kiln; (*b*) exact duplication of the physical structure of the laboratory-prepared brick with that of the manufactured brick could not be expected, due to use of small-scale laboratory apparatus; (*c*) the same batch materials as furnished by the manufacturer would rarely, if ever, be used in the manufacture of fire bricks by the three methods, though it is quite common practice to use the same batch composition for bricks prepared by the dry-press and stiff-mud processes. However, it was believed that information of value would be obtained from this study not only to compare with test data of manufactured brick, but also to learn what effect a variation in the structure would have on certain physical properties. A photomicrograph of a specimen cut from burned bricks (batch P) made by each of the three methods of manufacture is shown in Figure 14. This particular batch material [25] is used commercially for making a stiff-mud brick. However, it is believed that the texture incident to each of the three processes of manufacture is well illustrated. The laminations in the brick prepared by the stiff-mud process are very pronounced, and the structure of the handmade brick appears to be considerably more dense than either of the bricks manufactured by the other processes. The brick made by the dry-press method shows probably the greatest uniformity.

The study of these bricks included the determination of: (*a*) Resistance to spalling, (*b*) absorption, (*c*) modulus of elasticity and transverse strength at 20° C. and at 550° C., (*d*) total linear burned shrinkage, and (*e*) linear thermal expansion from 20° to 1,000° C.

---

[24] A description of the various methods of manufacture of fire-clay brick may be found in B. S. Circular No. 282, Fire-Clay Brick. Their Manufacture, Properties, Uses, and Specifications.

[25] There is very little difference in composition between this manufacturer's batch materials used for brick prepa.ed by the stiff-mud and handmade processes.

2. TEMPERING WATER

The "tempering" or "conditioning water"—that is, the percentage of water considered as desirable for securing proper molding of the laboratory-prepared fire bricks—is given in Table 12. The loss in weight on heating a finished brick at 110° C. for approximately 18 hours was considered as the water necessary for molding. It was found that the water required for molding bricks from the various batch materials by the (*a*) dry-press method ranged from a low of 6.3 per cent to a high of 13.7 per cent, (*b*) stiff-mud-extruded process ranged from 10.9 to 24.1 per cent, and (*c*) handmade method ranged from 13 to 29.2 per cent.

Table 12.—*Data determined on fire-clay brick made in the laboratory from prepared batch materials furnished by the manufacturer*

Laboratory key letter	Method of preparation [1]	Tempering water	Linear burned shrinkage in per cent of wet length	Absorption in per cent of dry weight	Average number of quenchings to cause failure	Total expansion at 1,000° C. [2]	Modulus of elasticity [3] at—		Modulus of rupture at—	
							20° C.	550° C.	20° C.	550° C.
		Per cent				*Inches/inch*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
A	DP	10.2	5.8	7.2	18	568	2,230	2,440	840	1,340
	HM	15.4	10.0	8.2	12	560	2,860	3,600	1,085	1,020
	SM	16.4	10.1	7.7	9	566	2,880	3,960	1,020	1,110
B	DP	9.1	5.5	6.7	17	442	1,640	1,780	740	715
	HM	12.4	8.4	9.0	19	448	3,050	4,280	1,275	1,550
	SM	16.5	10.4	7.7	17	432	2,230	3,240	820	920
C	DP	6.4	3.5	9.3	18	442	2,310	2,075	985	830
	HM	14.2	8.2	11.5	18	449	2,740	2,700	1,015	1,000
	SM	13.0	8.4	9.4	9	470	1,860	1,800	680	620
D and N	DP	7.9	6.8	6.3	5	622	2,000	3,450	965	1,370
	HM	14.8	12.1	5.3	1	656	1,810	7,040	2,400	1,920
	SM	17.1	13.2	4.4	2	627	4,990	6,030	2,050	2,400
E and F	DP	7.1	6.4	5.3	6	508	1,990	3,860	1,140	1,710
	HM	16.1	13.6	4.9	3	607	5,090		1,290	
	SM	19.7	14.2	2.9	2	570	4,920	7,230	2,600	2,530
G	DP	11.2	3.1	14.1	7	654	830	1,260	450	690
	HM	18.1	6.9	16.1	9	640	1,500	1,380	875	940
	SM	22.0	8.2	15.3	8	643	1,390	1,680	755	1,045
H	DP	11.8	2.0	14.4	6	746	240	340	365	360
	HM	16.3	5.5	17.3	9	736	440		360	
	SM	23.9	9.6	16.1	11	717	170	320	150	335
I	DP	7.6	5.1	6.7	20	529	1,010	1,660	620	780
	HM	13.3	9.3	7.1	15	531	3,110	4,090	1,265	1,420
	SM	15.4	10.0	7.1	28	526	1,625	2,200	810	975
J	DP	7.6	4.6	5.1	3	412	6,430	6,530	1,590	1,945
	HM	16.1	10.0	4.9	3	412	5,330	8,100	1,625	1,590
	SM	20.1	10.4	3.9	3.	416	5,300	6,700	1,670	1,740
K and L	DP	8.0	5.7	7.1	16	475	2,810	2,710	1,000	910
	HM	12.3	8.4	7.6	13	484	5,180	6,270	1,526	1,635
	SM	16.3	11.2	6.7	16	499	2,550	2,830	1,028	1,135
M	DP	6.3	3.3	8.0	6	419	3,410	5,050	1,030	1,500
	HM	10.9	5.5	8.6	7	435	4,910	3,920	890	1,075
	SM	14.5	7.6	7.7	5	447	4,530	4,830	1,335	1,195
P	DP	13.1	3.9	14.6	2	622	550	740	390	545
	HM	24.1	8.9	13.6	3	586	1,420	1,670	865	955
	SM	29.2	12.4	13.9	3	610	1,100	1,320	485	620
Q	DP	10.7	10.4	4.8	24	445	2,700	3,390	955	1,065
	HM	24.5	10.4	6.1	28	453	4,880	5,470	1,270	1,460
	SM	24.2	11.5	5.8	33	435	3,440	2,700	975	845
R	DP	13.7	5.3	10.9	7	595	1,660	2,280	840	930
	HM	22.2	6.7	11.8	4	617	3,030	3,970	870	1,325
	SM	25.4	11.2	11.9	8	579	1,960	2,390	725	900

[1] DP, HM, SM, refer to dry press, handmade, stiff mud, respectively.
[2] Values to be multiplied by 10^{-5}.
[3] Values to be multiplied by 10^{3}.

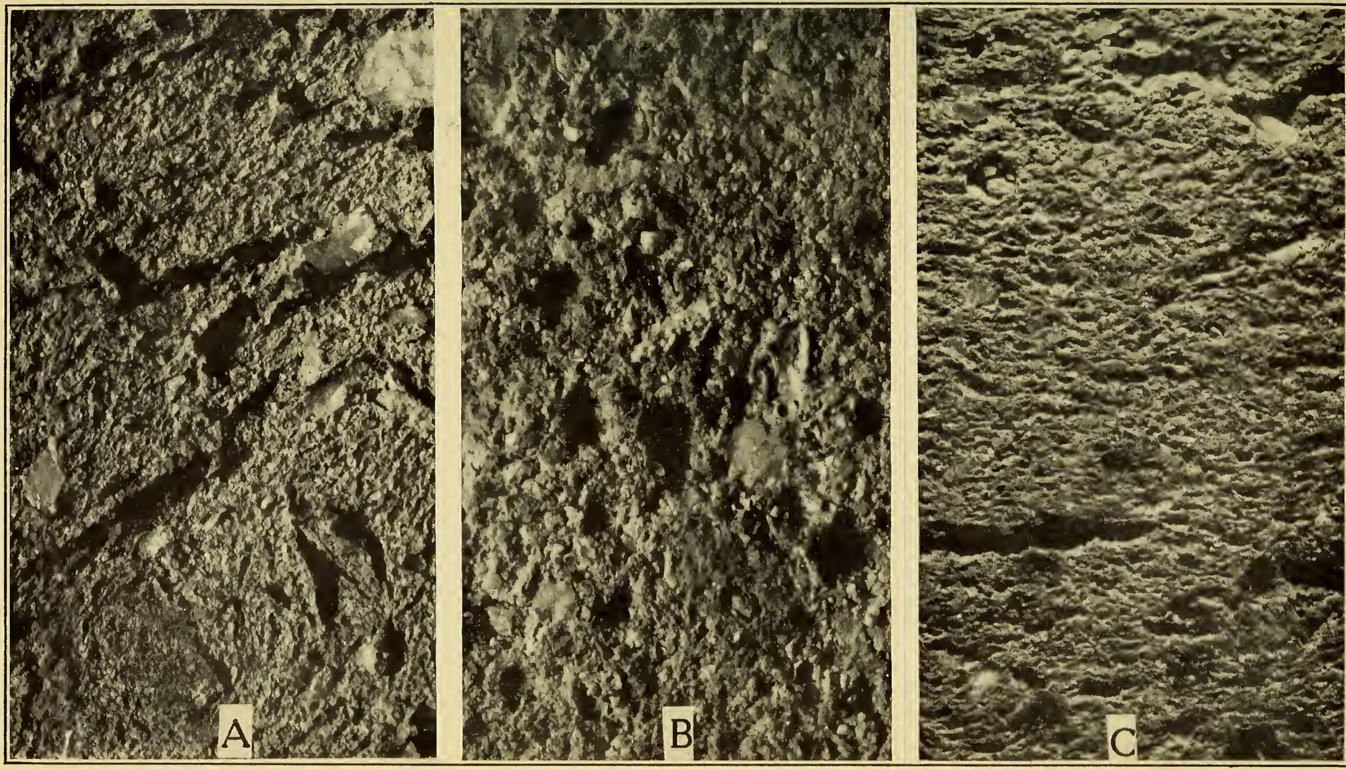

Figure 14.—*Photomicrograph, (4.5 diameters), showing structure of bricks made in the laboratory from a manufacturer's green batch material*

(A) is a section cut from a brick made by the stiff-mud method; (B), dry-press; and (C), handmade.

FIGURE 15.—*Types of failures of bricks when subjected to the water-quenching test*

The bricks were made by the following methods: (1), Stiff mud extruded; (2), handmade; (3), dry-press.

3. THERMAL SPALLING TEST

The results of the quenching test as conducted on a total of 42 different sets of 5 bricks each are given in Table 12. These results show (1) the average number of quenchings required to cause failure to range from 1 to 33; (2) those bricks (with one exception) with alumina content over 38 per cent have considerably greater resistance to spalling than those containing less than 38; and (3) although some sets show little difference in spalling resistance between bricks prepared by the different methods, others show almost 100 per cent difference.

A photograph of bricks prepared by the three methods from the same raw batch material and subjected to the thermal shock test is given in Figure 15. This illustrates well the types of spalling considered representative of fire-clay brick manufactured by the stiff-mud, handmade, and dry-press processes.

4. MODULI OF ELASTICITY AND RUPTURE

The modulus of elasticity and transverse strength of specimens cut from the 42 different bricks were determined at 20° and 550° C., and are given in Table 12, with the exception of the results for the handmade specimens E and H, at 550° C. There is a wide range in the values both at 20° and at 550° C., for elasticity and strength. The lowest value for modulus of elasticity obtained on specimen H (stiff-mud process) was 176,000 lbs./in.^{2}, and the lowest modulus of rupture, also obtained on this specimen was 150 lbs./in.^{2}, both values determined at approximately 20° C. The highest modulus of elasticity, found on specimen J (handmade process) at 550° C., was 8,100,000 lbs./in.^{2} and the highest modulus of rupture, found on specimen E (stiff-mud process) at 20° C., was 2,600 lbs./in.^{2} With few exceptions, it was found that the material gave higher values for both modulus of elasticity and transverse strength at 550° C. than at 20° C.

5. LINEAR BURNED SHRINKAGE

The linear burned shrinkage in per cent of length when wet is included in Table 12 with the other data determined on these bricks. The range in shrinkage, for all the groups, is from 2.0 to 14.2 per cent. The greatest range in shrinkage for any individual group representing specimens prepared from one batch composition by three different methods is from 6.4 to 14.2 per cent.

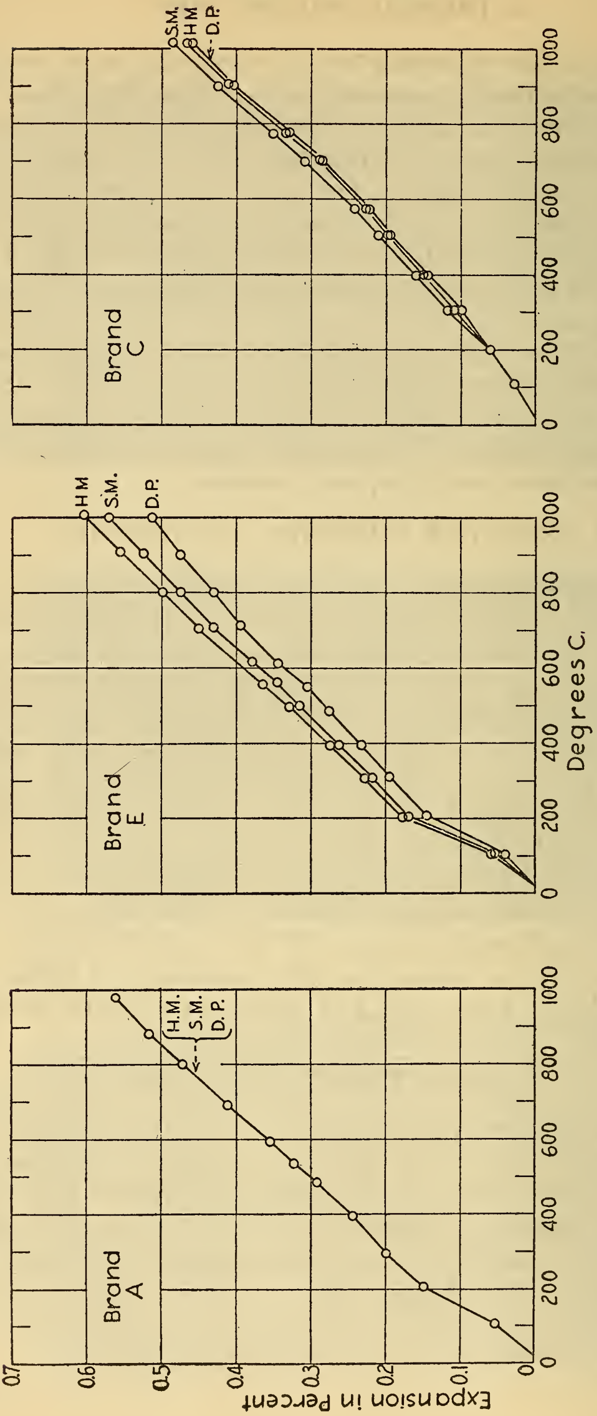

FIGURE 16.—*Curves showing linear thermal expansions of bricks made in the laboratory by three methods, namely, stiff-mud-extruded (S. M.); handmade (H. M.); and dry-press (D. P.) from manufacturers' prepared "green batch"*

6. LINEAR THERMAL EXPANSION

No detailed data are presented on thermal expansion observations of laboratory-made bricks since the curves obtained for these materials closely parallel those observed on the fire bricks furnished by the manufacturers of the corresponding raw batch materials. However, a number of curves are given in Figure 16 to show either what effect the structure of the bricks may have on this property or that the material from which the bricks were made was nonhomogeneous, causing a variation in expansions as observed.

The graph on the left in Figure 16 shows the curves obtained on laboratory-made brick corresponding to brand A. This is the only instance in which observations on bricks made from the same batch material by the three different processes were identical throughout the entire range of temperature from 20° to 1,000° C. This is especially noteworthy, since the bricks spalled in the quenching test after 9, 12, and 18 dips for the handmade, stiff-mud, and dry-press processed bricks, respectively. In addition, the difference in absorption was only 1 per cent, and the inflexion shown in the curve between 100° and 200° C. indicates that an appreciable quantity of quartz may have been converted to cristobalite.

The center graph of Figure 16 shows the expansion curves obtained on laboratory-made bricks corresponding to brand E. These curves show the greatest difference in thermal expansion determinations on bricks made from the same batch material by the three different processes. The total expansion at 1,000° C. of the brick made by the handmade process is approximately 20 per cent greater than the total expansion of the brick made by the dry-press method. An examination of the thermal expansion curves for these bricks shows that a good portion of this difference in expansion is caused by the greater inflexion of the curve at approximately 200° C. for the handmade bricks, possibly due to more of the quartz originally present having been converted to cristobalite. The brick made by the dry-press method still shows quite an appreciable inflexion between 550° and 600° C. Table 12 gives the absorption of the brick made by the handmade process as 2.9 per cent, and the brick made by the dry-press process as 5.3 per cent. This would possibly indicate that the conversion of quartz to cristobalite may be accelerated in the brick of the lower absorption, due to the probability of the fluxes being in more intimate contact with the quartz.

The graph on the right in Figure 16 shows the curves obtained on laboratory-made brick corresponding to brand C. These curves are given to illustrate the difference in total expansion that may occur in bricks having little or no free quartz and are molded by the three different methods. The difference in expansions may be due to either errors in sampling or to the structure of the material.

7. LINEAR THERMAL EXPANSION AND RESISTANCE TO SPALLING

The total observed linear thermal expansion at 1,000° C. for the 42 specimens of laboratory-made brick are given in Table 12. The greatest variation in the data for any one series of bricks made by the three different methods occurs in those bricks prepared from batch materials having a relatively large percentage of free or converted quartz present in a very finely divided condition. This may be expected, since the method of preparation of the bricks in these cases would have slightly more influence on the speed of reactions taking place during heating than in those bricks having only a small percentage of free quartz or if the quartz is present in comparatively coarse grains. Although in a number of cases there appears to be little or no relation between the total expansion and the resistance to spalling for any series of bricks made by the three methods, there are a large number of instances where a definite relation is apparent between these two properties. Typical examples that show this relation are the bricks identified by letters G and H. In a number of cases only two of the three sets in any one series show this relation. Groups E and M may be cited as examples.

VI. SUMMARY

The materials furnished by manufacturers of refractories for this study include 17 different brands of fire-clay bricks, 14 green batches, 26 fire clays, and 3 samples of quartz and silica sand.

The chemical analyses of the fire bricks and fire clays are reported, and the results of such determinations as absorption, pyrometric cone equivalent values, thermal spalling, and sieve analysis of grog used in green batch materials are recorded in a series of tables. The thermal expansions of the fire clays fired at 1,400° C. and those of the fire bricks "as received" from the manufacturer and after reheating in the laboratory kilns at 1,400°, 1,500°, and 1,600° C. are given, and the materials are classified into groups according to the type of expansion. In addition, the modulus of elasticity and transverse breaking strength of the bricks have been determined not only at several temperatures, but also after the brick had received several different heat treatments.

These data show that the thermal expansions of the majority of bricks decrease as the temperature of firing is increased. This would lead to the conclusion that interstructural stresses, which may be caused by differences in the thermal expansions initially present between materials entering into the manufacture of a brick, are gradually reduced.

Data are presented which indicate that the thermal expansion of the finished brick may not necessarily be the average of the expansions of the clays entering into its composition.

The moduli of elasticity of the bricks were generally much greater when tested at 550° C. than when tested at 20° C. At 1,000° C. the modulus of elasticity was less than results obtained at either 20° or 550° C.; that is, the bricks became less rigid and more subject to plastic deformation. The modulus of elasticity and transverse strength increase as the temperature of firing of the bricks is increased. The increasing percentage of glass formed would cause this behavior.

Resistance of fire bricks to spalling on an average decreased with increase of modulus of elasticity and increase of thermal expansion.

Data are given to show that sufficient differences exist in the physical properties of bricks of the same brand to cause large variations in the number of quenchings required to cause spalling.

Bricks were made in the laboratory by the dry-press, stiff-mud-extruded, and handmade methods from manufacturer's green batch materials. Test results indicated no apparent relation between method of preparation of bricks and their thermal expansion, but there is direct relation between expansion and resistance to spalling.

An empirical relation is given which expresses the resistance of fire-clay brick to spalling as varying directly as the modulus of rupture and grog content and inversely as the modulus of elasticity and coefficient of expansion.

WASHINGTON, February 4, 1929.

73113°—29——8