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DEFORMATION AND YOUNG'S MODULUS OF FIRE-CLAY BRICK IN FLEXURE AT 1,220° C

Raymond A. Heindl and William L. Pendergast

ABSTRACT

The plastic and elastic deformations of 17 brands of fire-clay brick were measured. The bricks were primarily of the type intended for high-heat duty and included bricks made by the stiff-mud, dry-press, and handmade methods of manufacture. Measurements were made at 1,220° C on 8 brands as received from the manufacturers and on the 17 brands after reheating at 1,400 and 1,500° C.

Young's modulus of elasticity of specimens in flexure and the modulus of rupture of the bricks as received and also after heating at 1,400° C were determined at 1,250° C.

The results of the deformation tests show that size and quantity of aggregate, ratio of flux to silica, and temperature of preheating before test bear an important relation to the plastic and elastic deformation of these bricks. Young's modulus of elasticity at 1,250° C is only a small fraction of that at ordinary temperatures.

CONTENTS

I. INTRODUCTION

The life of some industrial furnaces depends upon the ability of the firebrick making up the lining to resist deformation at operating temperatures. The use of heat-insulating materials on installations where they have not been formerly used, such as, for example, roofs of open-hearth furnaces and certain types of heat-treating furnaces, has greatly increased the possibility of plastic deformation of the fire-clay brick exposed directly to the heat of such furnaces. The reason is that insulation results in increasing the average temperature of the firebrick as compared with uninsulated firebrick.

The liability of brick to deform under load at working temperatures was recognized [1] long before insulating materials had gained their present popularity. The present standard method [2] of measuring deformation of fire-clay brick prescribes that the brick be set on end under a load of 25 lb/in.^{2} and heated for 1½ hours at 1,100, 1,300, 1,350, or 1,450° C, depending on the service requirements. The method is such as to preclude results of high precision and therefore was not suitable for this study. It was planned to determine, with a reasonable degree of accuracy, the total deformation (both plastic and elastic) of numerous brands of brick under controlled conditions of temperature, time, and load.

Values for the plastic deformation at 1,000° C of fireclay bricks in flexure were given in an earlier report.[3] The value of similar information obtained closer to the operating temperatures of furnaces is evident; consequently, a study was undertaken in which the temperature of test was 1,220° C. This was found to be the highest temperature at which all specimens could be tested.

The strength and Young's modulus of elasticity for most high-heat duty fire-clay brick at high temperatures are small in comparison with those obtained at room temperature. The resistance of bricks to deformation at high temperatures is probably due largely to the nature and quantity of the glassy bond. The proportion, type, and sizes of the aggregate, as well as the compactness of the entire structure, also have a decided bearing on the total deformation. As the temperature of test of a fire-clay brick is increased above that at which the glassy phase begins to soften, a greater percentage of the total deformation will be due to plastic flow and the resistance to deformation must then depend mainly on the aggregate and the crystal growths. Results of preliminary experimental work indicated that the temperature at which practically all of the test specimens showed sufficient resistance to deformation to permit measurement of their elastic properties was about 1,250° C. The same temperature of test for all materials was desirable so that the data obtained would be comparable.

II. MATERIALS

The fire-clay bricks for this study were left-over samples of the brands discussed in an earlier publication.[4] It was necessary to obtain additional samples of some of the brands.

1. CHEMICAL COMPOSITION

Each sample for chemical analysis was taken from the same brick as the deformation specimen. The results of the analyses are given in table 1. In general, the methods described by Finn and Klekotka,[5]

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[1] A. V. Bleininger and G. H. Brown, *The testing of clay refractories with special reference to their load-carrying capacity at furnace temperatures.* BS Tech. Pap. **1** (1910-12) T7.

[2] Standard method of test for refractory materials under load at high temperatures. American Society for Testing Materials Book of Standards for 1936, pt. 2, p. 224.

[3] R. A. Heindl and W. L. Pendergast, *Progress report on investigation of fire-clay bricks and the clays used in their preparation.* BS J. Research **3**, 691 (1929) RP114.

[4] R. A. Heindl and W. L. Pendergast, *Progress report on investigation of fire-clay bricks and the clays used in their preparation.* BS J. Research **3**, 691 (1929) RP114.

[5] *On a modified method for decomposing aluminous silicates for chemical analysis.* BS J. Research **4**, 809 (1930) RP180.

and Lundell and Hoffman[6] were followed. The silica ranges from 48.35 to 81.76 percent, the alumina from 15.01 to 43.81 percent, and the total flux (by difference) from 3.09 to 7.95 percent. This range of values includes most fire-clay bricks.

TABLE 1.—*Chemical composition of firebrick*

Brand	SiO_2	Al_2O_3	Total[1] flux (by difference)	$Fe_2O_3+TiO_2$	P_2O_5	$\frac{\text{Total flux}}{\text{Total silica}}$
	%	%	%	%	%	
A	57.52	36.70	5.50	3.84	0.05	0.096
B	53.95	38.82	6.89	4.41	.11	.128
C	50.29	43.50	6.05	4.21	.14	.120
D	57.45	36.67	5.64	3.54	.13	.098
E	55.12	39.38	5.34	2.86	.15	.097
F	58.73	35.37	5.54	2.74	.36	.094
G	66.50	30.09	3.23	2.48	.06	.049
H	81.76	15.01	3.09	2.22	.04	.038
I	56.78	35.77	7.03	4.22	.09	.124
J	60.53	31.78	7.43	3.68	.13	.123
K	54.80	38.00	7.02	4.12	.13	.128
L	55.82	36.99	6.89	3.92	.06	.123
M	53.94	37.77	7.95	4.76	.07	.147
N	56.24	38.75	4.75	3.42	.12	.084
P	65.59	26.83	3.34	1.98	.04	.048
Q	48.35	43.81	7.78	2.64	1.68	.161
R	54.89	38.92	5.95	4.22	.09	.108

[1] Difference between the sum of the silica, the alumina, the ignition loss, and 100.

2. PYROMETRIC CONE EQUIVALENTS

The pyrometric cone equivalents (pce or softening points) were determined according to the ASTM[7] standard method, serial designation C24–35. The values are given in the third column of table 2. 15 of the 17 brands of fire-clay brick have a pce of 31 or higher. This indicates that, with one exception, *J*, the materials are of a grade of refractoriness that would preclude appreciable vitrification when reheated at 1,400° C for 5 hours.

3. SIZES OF AGGREGATE AND GROG

The method of obtaining the percentage and size of particles making up the aggregate in the raw batch materials was discussed in an earlier report.[8] For reference purposes the percentage of total particles coarser than a no. 40 sieve (United States Standard Series) for each raw batch of the various brands of brick is given in table 2, column 4. The particles retained on the no. 40 sieve ranged from 19 to 61 percent.

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[6] *Analysis of bauxite and of refractories of high alumina content.* BS J. Research **1,** 91 (1928) RP5.

[7] American Society for Testing Materials, Book of Standards for 1936, pt. 2, p. 229.

[8] BS J. Research **3,** 691; (1929) RP114.

TABLE 2.—*Deformation data of fire-clay brick tested at 1,220° C*

Brand	Method of manufacture [1]	Pyrometric cone equivalent	Aggregate retained on sieve no. 40	Deformation of specimens tested as received [2] from manufacturer			Deformation of specimens tested after reheating at 1,400° C for 5 hours				Deformation of specimens tested after reheating at 1,500° C for 1 hour			
				Total after 2½ hr, loaded	Residual after 1 hr, unloaded	Elastic after 60 min [3]	Total after 2½ hr, loaded	Residual after 1 hr, unloaded	Elastic after [3]—		Total after 2½ hr, loaded	Residual after 1 hr, unloaded	Elastic after [3]—	
									5 min	60 min			5 min	60 min
		Cone	%	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*
A	*HM*	33	52	--------	--------	--------	0.0218	0.0171	0.0027	0.0046	0.0134	0.0103	0.0019	0.0031
B	*HM*	32	53	--------	--------	--------	.0141	.0111	.0023	.0030	.0166	.0137	.0018	.0029
C	*DP*	33	59	--------	--------	--------	.0438	.0381	.0040	.0057	.0111	.0086	.0018	.0025
D	*DP*	31–32	43	0.1917	--------	--------	.0142	.0111	.0018	.0031	.0083	.0062	.0012	.0021
E	*DP*	32–33	40	--------	--------	--------	.0241	.0208	.0022	.0033	.0098	.0079	.0012	.0019
F	*SM*	31	40	.0318	0.0282	0.0035	.0096	.0077	.0012	.0019	.0064	.0051	.0008	.0013
G	*HM*	32–33	30	.0206	.0172	.0034	.0102	.0084	.0013	.0018	.0040	.0023	.0009	.0017
H	*HM*	31	22	.0054	.0039	.0016	.0031	.0016	.0008	.0015	.0009	.0000	.0005	.0009
I	*HM*	31	51	--------	--------	--------	.0472	.0398	.0046	.0074	.0214	.0179	.0024	.0035
J	*SM*	30	31	--------	--------	--------	.0360	.0323	.0024	.0037	.0229	.0192	.0023	.0037
K	*SM*	32	44	--------	--------	--------	.0296	.0258	.0027	.0038	.0150	.0121	.0013	.0029
L	*DP*	33	44	.0986	--------	--------	.0263	.0230	.0023	.0033	.0139	.0111	.0017	.0028
M	*HM*	33	47	--------	--------	--------	.0192	.0167	.0020	.0025	.0120	.0091	.0020	.0029
N	*SM*	32	43	.0480	.0439	.0040	.0080	.0062	.0011	.0022	.0060	.0048	.0008	.0012
P	*SM*	30–31	19	.0048	.0031	.0017	.0035	.0024	.0007	.0011	.0022	.0003	.0005	.0019
Q	*DP*	33	61	--------	--------	--------	.0574	.0517	.0029	.0057	.0190	.0150	.0031	.0040
R	*HM*	32–33	31	.0086	.0063	.0022	.0062	.0044	.0009	.0018	.0066	.0045	.0012	.0021

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[1] *HM, SM, DP* refer to handmade, stiff-mud, dry-press processes of manufacture, respectively.

[2] With the exception of those shown, specimens ruptured within 15 minutes after application of load. *D* and *L* failed after 80 and 50 minutes, respectively.

[3] Representing the elastic recovery at the end of 5 minutes and 60 minutes after unloading.

4. POROSITY

The porosity determinations were made in accordance with the test method adopted by the American Ceramic Society,[9] except that the specimens were boiled for 5 hours and permitted to cool overnight. The specimens (1 by 1 by 2 in.) were cut from the bars after deformation tests had been completed. The results given in table 3 are for reference purposes only.

TABLE 3.—*Modulus of rupture, Young's modulus of elasticity, and porosity of fire-clay brick tested at 1,250° C*

Brand	Porosity		As received from manufacturer		After reheating at 1,400° C for 5 hours	
	As received [a]	After reheating at 1,400° C	Modulus of rupture	Modulus of elasticity	Modulus of rupture	Modulus of elasticity
	%	%	lb/in.^{2}	1,000 lb/in.^{2}	lb/in.^{2}	1,000 lb/in.^{2}
A	27.7	22.0	85	77	520	233
B	22.0	20.4	200	174	765	372
C	21.6	20.0	55	76	500	238
D	16.4	15.3	230	159	860	256
E	16.2	15.6	220	144	945	361
F	14.4	9.6	830	277	1,450	535
G	31.8	29.0	720	201	870	275
H	36.6	30.4	640	254	905	621
I	24.8	18.9	145	86	485	130
J	16.1	9.6	[b] 195	[b] 134	380	147
K	21.0	18.0	105	116	700	309
L	17.0	12.0	195	150	600	228
M	22.1	20.5	150	137	710	347
N	20.0	12.7	1,060	314	1,600	742
P	25.2	24.0	2,045	522	1,850	975
Q	16.3	14.5	[c] 650	[c] 156	130	233
R	29.8	22.0	445	229	1,170	602

[a] Specimens used had been tested at 1,250° C for deformation.
[b] Tested at 1,150° C.
[c] Tested at 1,100° C.

III. SPECIMENS

The specimens for comparing the effect of heating at different temperatures on plastic deformation represent only one brick of each brand because of the wide variation in certain properties between firebrick of the same brand, which has been discussed by Heindl.[10] The specimens measured 1 by 1 by 9 in. Two of the 1- by 9-in. surfaces of each specimen were outside surfaces of the brick. That surface of the specimen which had been a portion of the 9- by 2½-in. surface of the brick was removed by grinding. One of the specimens in each case was set aside for testing without reheating, a second was reheated at 1,400° C for 5 hours, and the third at 1,500° C for 1 hour.

In addition, specimens from more than one brick were tested, after reheating at 1,400° C for 5 hours, to obtain data comparing variation in total deformation between bricks of the same brand.

For Young's modulus of elasticity and strength, the specimens do not necessarily represent either one brick or edge specimens as was the case with the plastic-deformation studies.

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[9] J. Am. Ceram. Soc. **11**, 456 (1928).

[10] A discussion of thermal spalling of fire-clay brick with relation to Young's modulus of elasticity, thermal expansion and strength. Am. Ref. Inst. Tech. Bul. no. 58 (May 1935).

IV. METHODS OF TESTING

1. DEFORMATION

The furnace and equipment for making measurements of the plastic deformations of firebrick have been described by Heindl and Pendergast.[11] The specimens were tested over an 8-inch span. The stress at the extreme fiber, exclusive of the weight of the loading clevis and specimen, was 6 lb/in^2. The temperature of the furnace was maintained at approximately 1,220° C (average of readings of two thermocouples) during the test and for 1 hour immediately preceding the application of the load. After the load was applied, gage readings were taken for a 150-minute period, the first four readings being taken at 5-minute intervals and the balance at 10-minute intervals. At the end of that time the load was removed and readings were taken at periodic intervals for 60 minutes to measure the elastic recovery of the material.

2. YOUNG'S MODULUS AND STRENGTH

The apparatus used for determining Young's modulus of elasticity as well as the transverse strength was the same as that used for determining the total deformation. In the present instance the furnace temperature as indicated by one thermocouple close to the specimen was 1,250° C. The specimens were under load for 5-minute periods and were permitted to recover after releasing each load for a 15-minute period. In general, the same types of curves were obtained as are illustrated in an earlier report,[12] although the time intervals for loading and unloading and the temperature of test were different.

The modulus of rupture was obtained after completion of the elastic measurements by gradually increasing the load until rupture occurred.

3. MICROSCOPIC ANALYSIS AND STRUCTURE

An examination with the petrographic microscope was made of 9 of the 17 brands of bricks. Thin sections were prepared from the same brick from which plastic-deformation specimens were taken; a section was made from the bricks as received from the manufacturer, a second and third after reheating at 1,400° C and at 1,500° C, respectively. The primary purpose of this examination was to obtain information regarding the content of glass and the extent and development of mullite due to the reheating.

The structure of each brand of brick was studied with 10-power binoculars. The purpose of this examination was to obtain information as to compactness of structure and type of aggregate as well as the general appearance of the bonding clay with the aggregate.

V. RESULTS AND DISCUSSION

1. DEFORMATION OF FIRE-CLAY BRICK

The values for total deformation of the bricks tested are given in table 2. The total deformation under load includes both the elastic and plastic deformations. After removal of the load a certain amount

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[11] *Young's modulus of elasticity at several temperatures for some refractories of varying silica content.* J. Research NBS **13**, 851 (1934) RP747.

[12] *Progress report on investigation of fire-clay bricks and clays used in their preparation.* BS J. Research **3**, 691 (1929) RP114.

of recovery takes place. The deformation remaining at the end of 1 hour is termed "residual deformation" and represents largely plastic deformation which took place during the test, while the recovery after removal of the load is termed "elastic deformation." These data show that a great portion of the elastic recovery takes place within the first 5 minutes after removal of the load.

Figure 1 shows typical curves of the deformation obtained on three brands of brick under load for 150 minutes. For all bricks the deflection increases with time. With removal of the load a fairly rapid recovery takes place immediately as indicated by the break in the curves at 150 minutes. The recovery thereafter continued to the end of the test but at a gradually reducing rate.

(a) EFFECT OF PARTICLE SIZE

The percentage of aggregates or particles in the raw brick batches not passing a United States Standard Sieve no. 40 are given in table 2. The range is from 19 to 61 percent, with the tendency for the highly siliceous clay batches to contain the lower percentages and the high flint clay batches to contain the higher percentages of aggregate.

Analysis of the deformation values obtained on 1 specimen of each of the 17 different brands reheated at 1,400° C indicated a direct relation between percentage of particles coarser than a no. 40 sieve and the total deformation. The coefficient of correlation,[13] 0.72, shows the existence of such a relation, which apparently ceases to exist after the specimens have been reheated at 1,500° C, owing to the reaction between the bond clay and the aggregate. The coefficient of correlation in this case was 0.14.

(b) EFFECT OF METHOD OF MANUFACTURE

Firebrick brands *E, F; D, N;* and *L, K* were furnished by three manufacturers. The raw batch for each pair was of the same composition, but the method of forming was different; that is, brands *F, N,* and *K* are stiff-mud bricks, whereas, *E, D,* and *L* are dry-pressed. However, the processes of forming *L* and *K* are somewhat modified. Consequently, the structure of *K* does not correspond to that of the typical stiff-mud brick. In the case of *F* and *N* the deformations are much less than for the corresponding brands *E* and *D* made by the dry-press process. Although L_{14} (brand *L* reheated at 1,400° C) [14] and K_{14} represent the dry-press and stiff-mud processes, respectively, there is no noticeable difference as far as appearance of the structure is concerned. This similarity in structure may account for the not great dissimilarity in deformation properties. Figure 2 shows F_{14}, a typical stiff-mud structure and E_{14}, a dry-pressed structure; R_{14} is a handmade brick. Figure 3 shows L_{14} as a "modified" dry-press brick and K_{14} as a "modified" stiff-mud brick, both from the same raw batch, and I_{14} as a loosely bonded handmade brick containing a large amount of aggregate.

Though not conclusive, the data (table 2) in general indicate that bricks of the dry-press type have uniformly high deformations; the stiff-mud type, with one exception, low deformations and the handmade deformations intermediate of the first two types.

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[13] Manual for Interpretation of Refractory Test Data. ASTM Standards on Refractory Materials (Feb. 1935).

[14] In this report the heat treatment any specimen received before test is indicated thus: *L*, as received; L_{14}, reheated at 1,400° C; L_{15}, reheated at 1,500° C.

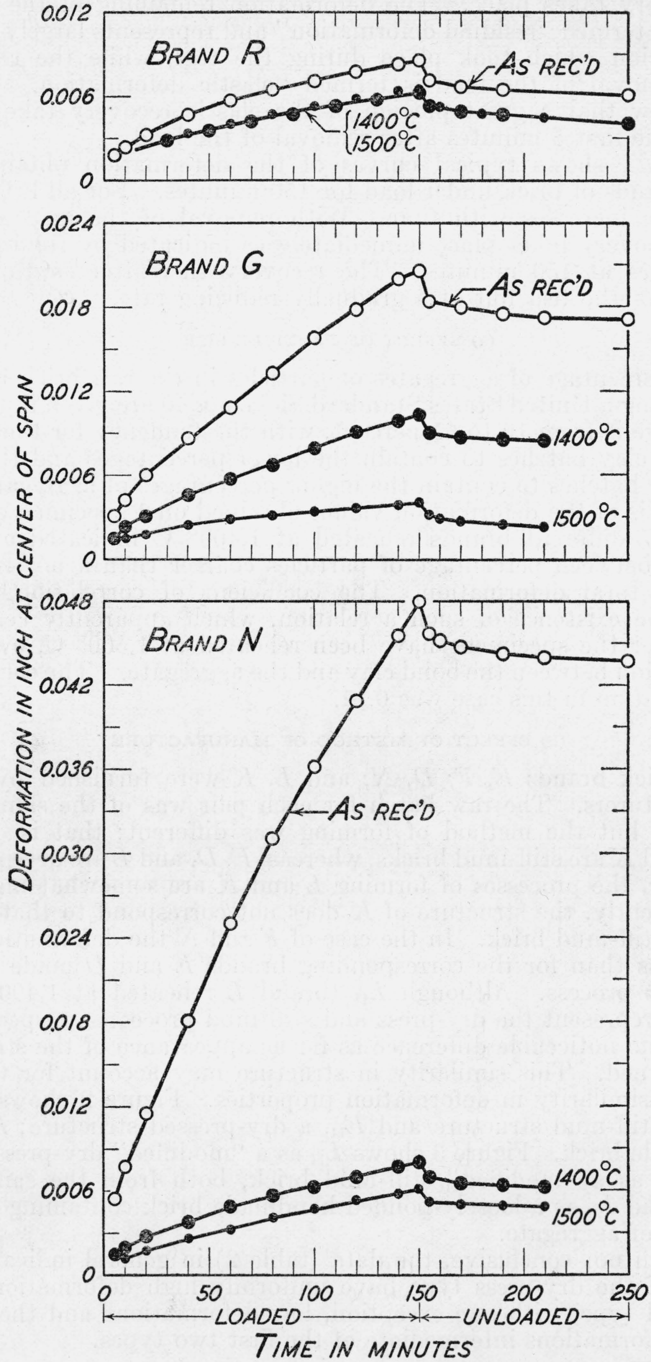

FIGURE 1.—*Effect of heat treatment on the deformation of different types of fire-clay brick.*

Deformation under load and recovery after removal of the load of fire-clay brick brands *R*, *G*, and *N* as received from the manufacturer and after reheating at 1,400° C and at 1,500° C as noted adjacent to each curve.

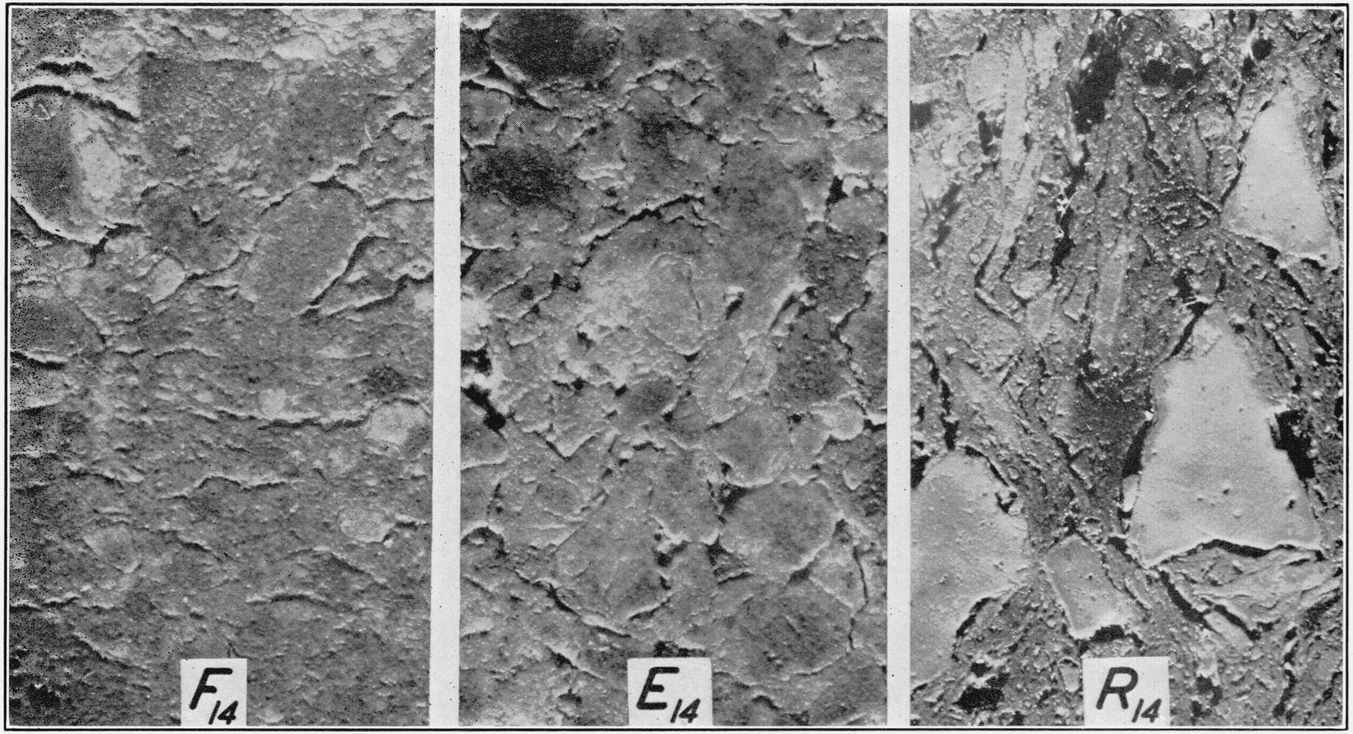

FIGURE 2.—*Semipolished section* (×12) *of firebrick brands F, E, and R reheated at 1,400°* C.

Brands *E* and *F* have the same composition and a very uniform structure, but the former, manufactured by the dry-press process, is considerably more open than the latter, which is manufactured by the stiff-mud process. *R*, manufactured by the hand-made process, shows a structure filled with more or less parallel channel pores.

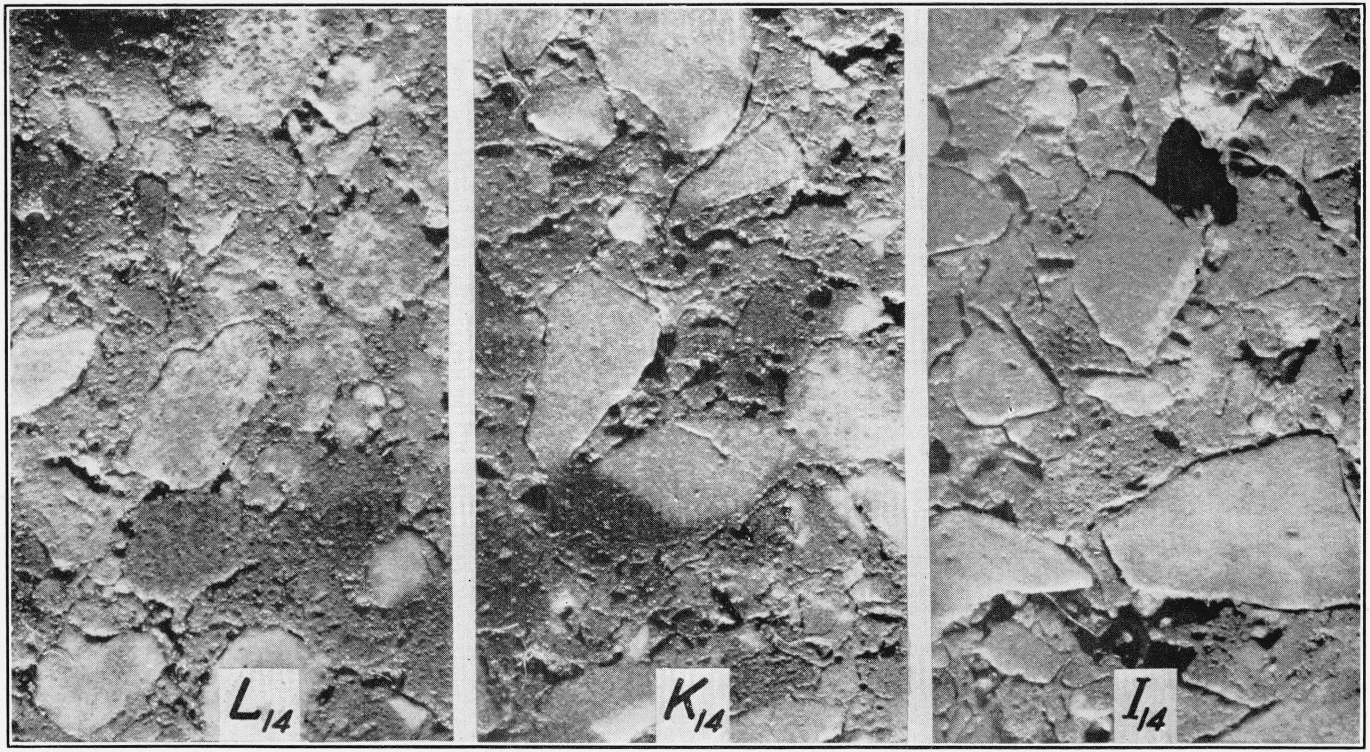

FIGURE 3.—*Semipolished sections* (× *12*) *of fire-clay brick brands L, K, and I after reheating at 1,400°* C.

L and *K* have the same composition. Although manufactured by modified dry-press and stiff-mud processes, no significant differences in structure were apparent. *I*, formed by the hand-made process, shows the flint-clay particles to have shrunk considerably more than the bond clay, which is not so apparent with *L* and *K*.

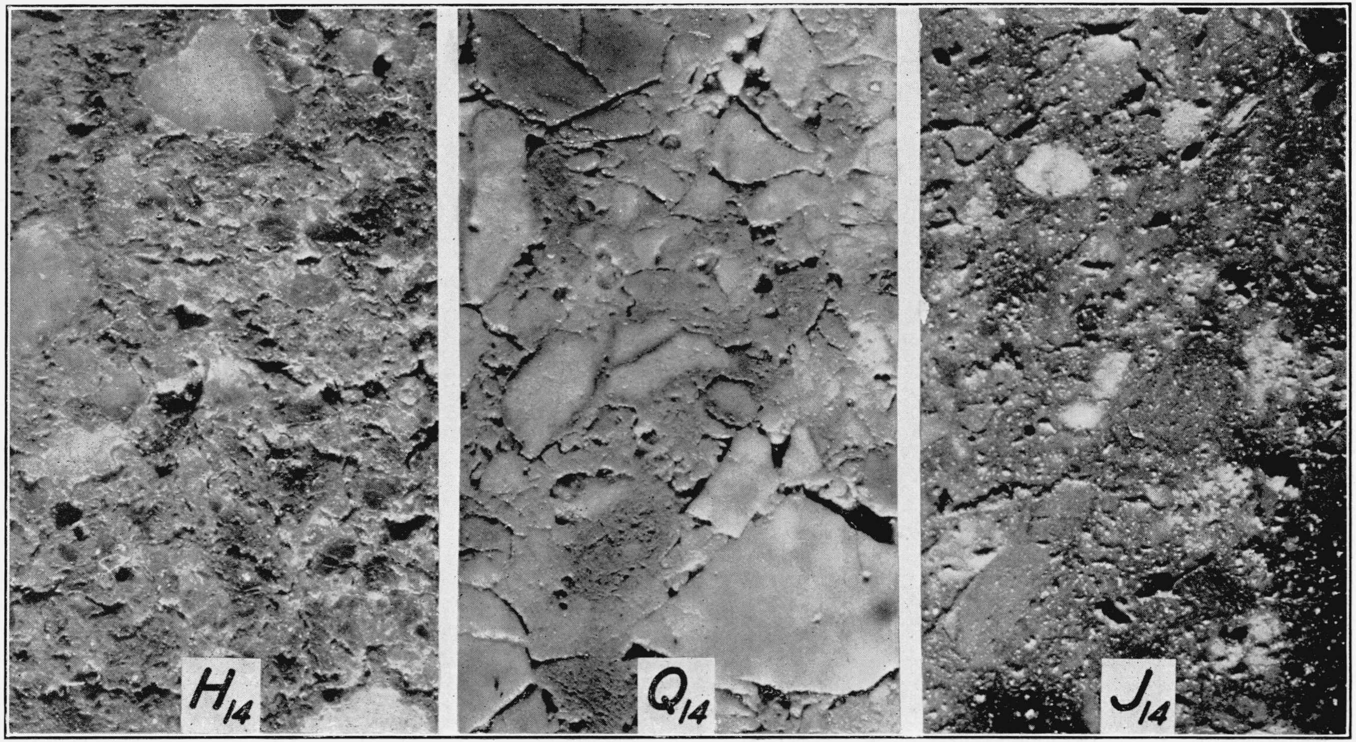

FIGURE 4.—*Semipolished sections (×12) of firebrick brands H, Q, and J after having been reheated at 1,400° C for 5 hours.*

H_{14}, a highly siliceous fire-clay brick with a skeleton of quartz particles, has very little deformation; Q_{14}, made from a single clay, has a high alumina content and a very high deformation when tested at 1,220° C. J_{14}, less refractory than either *H* or *Q*, is almost a monolithic structure and has a high deformation.

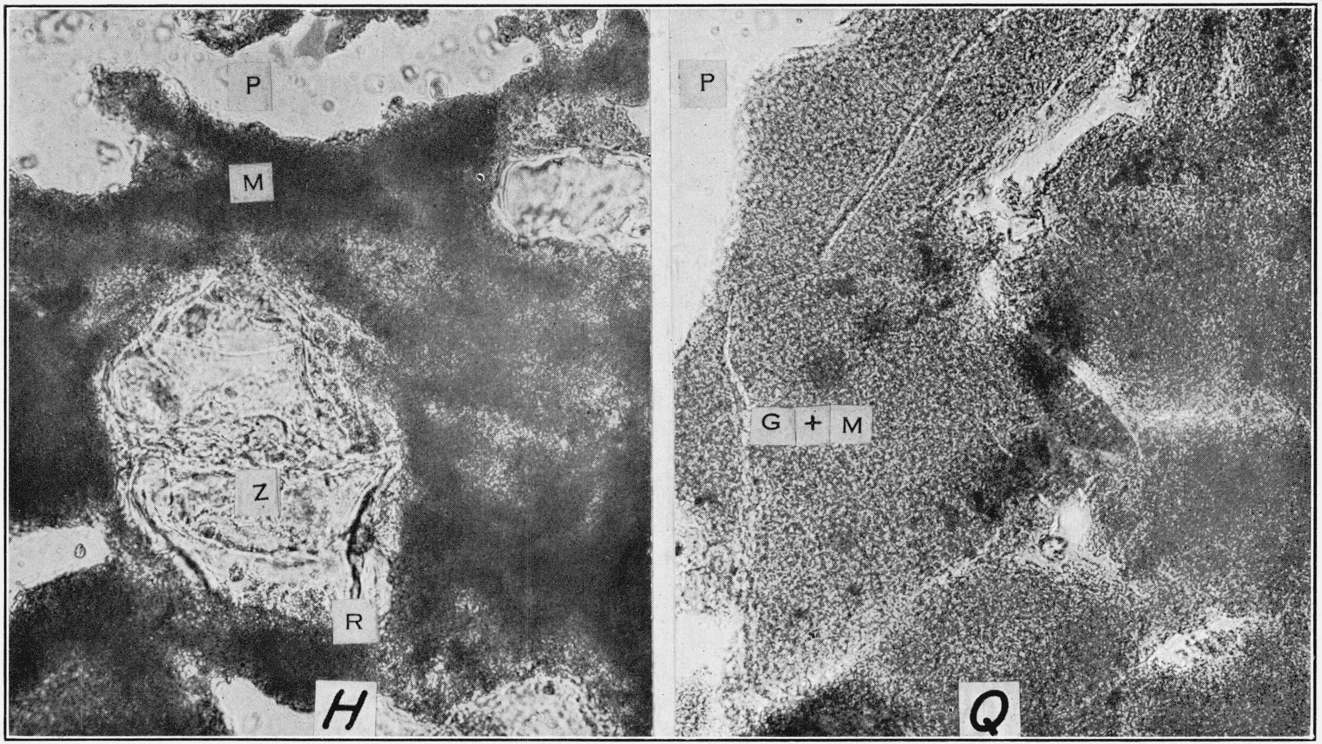

Figure 5.—*Section of firebrick brands H and Q (ordinary light, ×430) as received from the manufacturer.*

H shows quartz crystals (small letter *Z*) with solution rim (*R*), appreciable development of mullite (*M*) in the clay bond, and very little glass in the area designated *M*. The high glass (light background *G*) content in the bonding material, almost complete absence of quartz crystals, and meager mullite (dark specks *M* in field of *G*) crystallization are noted in brand *Q*. The light areas designated *P* in both sections are pores.

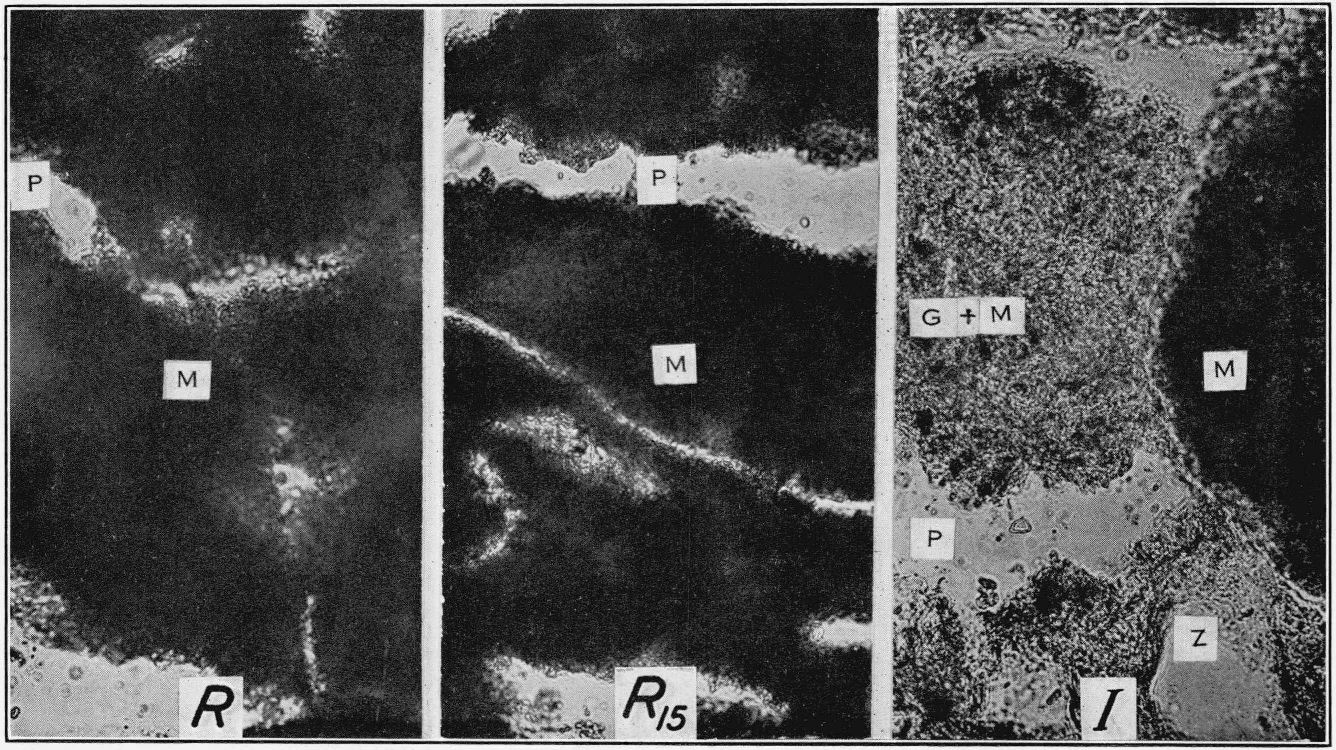

FIGURE 6.—*Section of firebrick brand R as received, and after heating at 1,500° C* (R_{15}) *and brand I as received (ordinary light, ×430).*

Both R and R_{15} show very little glass (only in evidence along edges of pores P), with mullite abundant (as indicated by dark areas M). R_{15} shows that reheating has changed the structure very little. Section I in comparison shows much glass (light background of $G+M$) with only a small amount of mullite (dark specks M in field of $G+M$) in the bond but an appreciable amount in the flint-clay grain (dark area M), possibly due to preheating before being compounded in the brick batch. Some quartz grains (Z) and pores (P) are in evidence. R has a low deformation and that of I is very high.

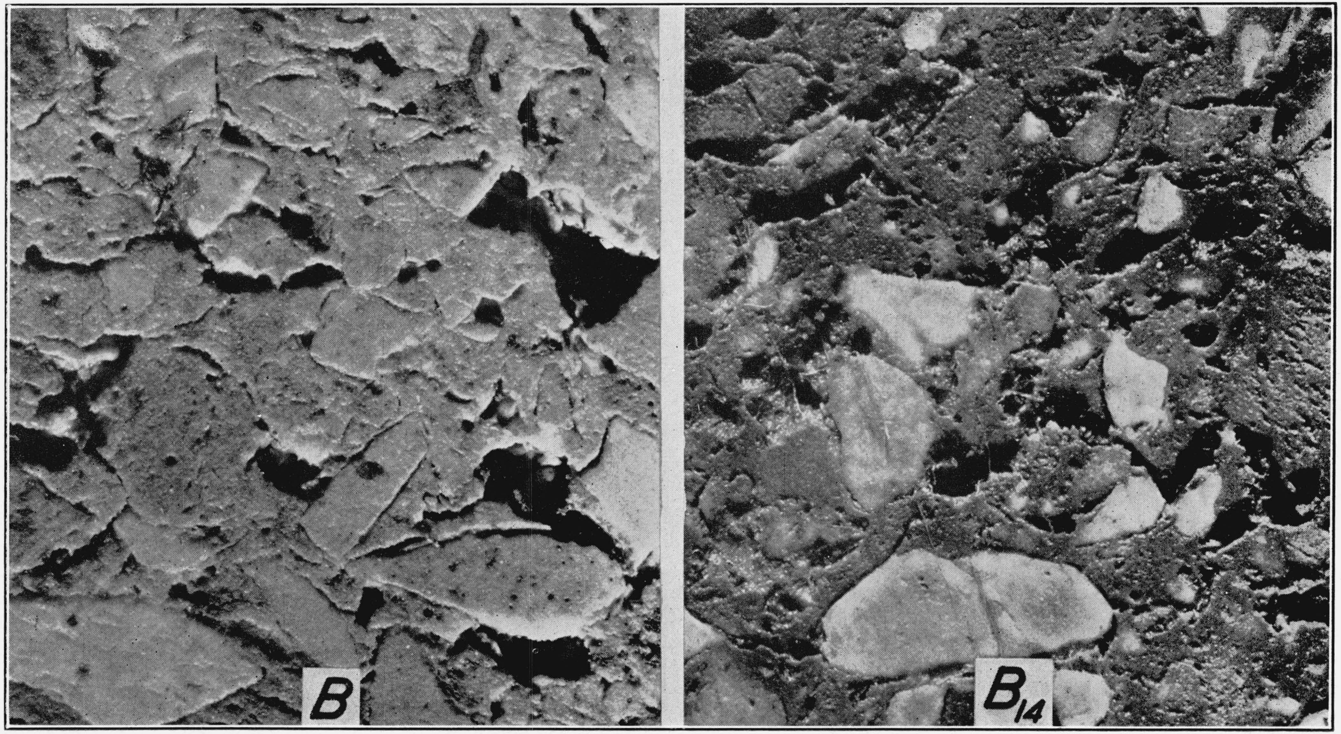

FIGURE 7.—*Semipolished section (×12) of fire-clay brick brand B as received from manufacturer and also after heating at 1,400°* C.

The effect of the reheating on the structure is evidenced by the welding of the semiflint-clay particles and bonding clay forming a monolithic structure in which flint-clay particles are fairly tightly embedded. The monolithic structure is filled with blebs.

(c) EFFECT OF TOTAL FLUX AND TOTAL SILICA

The data obtained are in agreement with the well-known fact that highly siliceous fire-clay bricks have less deformation at high temperatures than do those bricks containing more alumina. The ratio of total flux to total silica is given in table 1. It is to be expected that up to a certain point a high percentage of flux will tend to lower the viscosity of the glass present in a refractory and this in turn will tend to increase the deformation.

A reasonably good relation was noted between total deformations obtained on bricks reheated at 1,400° C and the ratio of total flux to total silica. Such a relation is also indicated by the coefficient of correlation which was found to be 0.84. Figure 4 compares the structure of H_{14}, a highly siliceous brick (81.76 percent of SiO_2) with a low ratio of flux to silica (0.038), and Q_{14} containing much less silica (48.35 percent) and a rather high flux to silica ratio (0.161). These two brands represent the extremes in total deformation. J_{14} has a low pce (30) and a fairly high flux to silica ratio (0.123). Since the petrographic examination of J_{14} showed mullite to be in abundance, the deformation is not as great as that in some of the others having a less-dense structure, as for example Q_{14}. Figure 5 also compares brands *H* and *Q* but under high magnification. *H* shows much less glass than *Q* and a high percentage of mullite. The bonding material in *Q*, on the other hand, is very glassy with mullite present in small quantities only.

(d) EFFECT OF HEAT TREATMENT

Table 2 gives data on 8 specimens as received and on 17 specimens which had been reheated at 1,400° C and a second series of 17 at 1,500° C. Nine specimens set up for test as received failed before their deformations could be observed. After reheating, however, all specimens could be tested. Only the typical examples for which curves are shown in figure 1 will be discussed.

Brand *R* does not deform greatly when tested as received nor does the extent of that deformation change greatly after reheating the specimens at either 1,400 or 1,500° C. Brand G, as received, has a moderately high deformation; after the reheating at 1,400° C the deformation decreases to about one-half and after the reheating at 1,500° C to about one-fifth of that of the as received specimen. Brand *N*, as received, had a high deformation, but after the reheating at 1,400° C its deformation was only a small fraction of that of the as received specimen and showed comparatively little further change after reheating at 1,500° C.

There are several reasons why brand *R* has high resistance to deformation. The petrographic examination showed that *R*, as received, contained very little glass and that mullite was in abundance. Reheating at 1,400° C and reheating at 1,500° C somewhat increased the content of mullite. Figure 6 shows brand *R* as received and after reheating at 1,500° C (R_{15}). An abundance of mullite is indicated in both cases by the dark (opaque) areas. Brand *R* contains many more or less elongated parallel (channel) pores as may be seen in figure 2, (low magnification of *R*). These pores are parallel to the direction of the applied load during the deformation test; therefore, it is believed that they did not have an appreciable effect on the deformation. R_{14} (fig. 2) shows also the tendency for the bond and aggregate to shrink toward one another; that is, the shrinkage is such that the bond clay and aggregate remain in fairly intimate contact. The narrow-channel pores in some cases are adjacent to the coarse angular clay particles, which may give an impression that shrinkage of the aggregate has been greater than the bonding material. But this is not the case, as was proved by an examination of the full-size specimen. The closing together of bond and aggregate naturally causes a body to be more resistant to deformation. Furthermore, *R* contains comparatively little coarse aggregate (31 percent) and the flux to silica ratio is not high.

Brand *G* (fig. 1) is of the highly siliceous type of brick. It has a low flux to silica ratio and a low percentage of coarse aggregate. The bond and aggregate are in close contact and the brick has a fairly compact but granular appearance.

An examination with the binoculars of brand *N*, also referred to in figure 1, showed a well-bonded, compact, and dense structure. There was a slight tendency for some of the aggregate to shrink from the bond. The percentage of coarse aggregate was intermediate between the extremes for all brands of bricks. The petrographic examination showed a very high glass content and some mullite in the original brick. The glass decreased and the mullite needles increased in size and quantity with the higher heat treatments. A few grains of quartz were observed. The decrease in deformation with the heat treatments was undoubtedly due to the decrease in glass and increase in quantity of mullite crystals.

Figure 7 shows the effect on structure after reheating at 1,400° C a loosely bonded handmade brick. This brick contains a high percentage of coarse aggregate which has an appearance of not being well mixed with the bond. Twenty-two percent [15] of the aggregate was retained on a no. 10 sieve. Because of the open structure, which is emphasized by the tendency of some of the aggregate to shrink from the bond, the as received specimen failed before the deformation could be observed. The bond clay had a pce of 26 and the petrographic examination showed some mullite needles and an appreciable discoloration of the glass due to a fairly high content of iron. After reheating at 1,400° C (B_{14}) the deformation could be readily measured and it was rather low compared with several of the others which had approximately the same ratio of flux to silica. This is difficult to explain. An abundance of mullite and the tightening and welding of the structure (see fig. 7) may be the cause of the comparatively low deformation. However, after the reheat at 1,500° C the deformation was actually greater which, although small, is the reverse order from that shown by other brands. Petrographic examination showed many blebs and many long needles of mullite in the glass adjacent to quartz particles. The specimen was highly stained with iron and many particles appeared overfired or vitreous.

Figure 8 shows the effect of heating brick made from one clay (all flint clay) at successively higher temperatures. Brand *Q* had the greatest percentage of aggregate (61 percent) retained on the no. 40 sieve. The aggregate, largely of medium size, was well distributed, angular, and formed the skeleton of the brick. The structure was compact, as evidenced by the porosity of 16 percent. The absence of low fluxing bonding materials was indicated by the pyrometric-cone

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[15] *Progress report on investigation of fire-clay bricks and the clays used in their preparation.* BS J. Research **9**, 691 (1929) RP114.

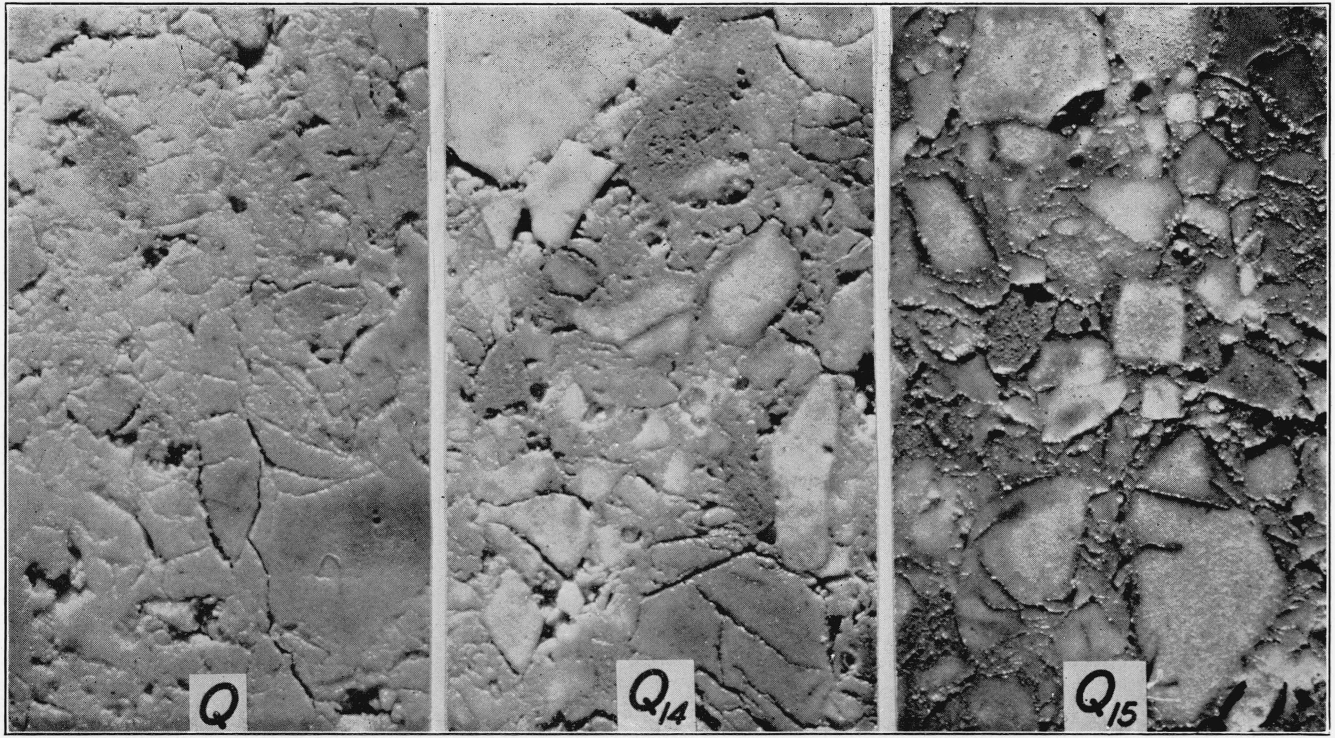

FIGURE 8.—*Semipolished sections (×12) of firebrick brand Q (made from one clay only) as received from the manufacturer and after reheating at 1,400° C (Q_{14}) and at 1,500° C (Q_{15}).*

Q is very compact, but lack of bonding strength is indicated by many hairlike cracks between the closely packed particles. Q_{14} shows shrinkage of coarsest particles to be slightly greater than the fine, and the hairlike cracks in the finer aggregate have disappeared. Q_{15} shows both coarse and fine material drawn closely together, and the whole appears well bonded.

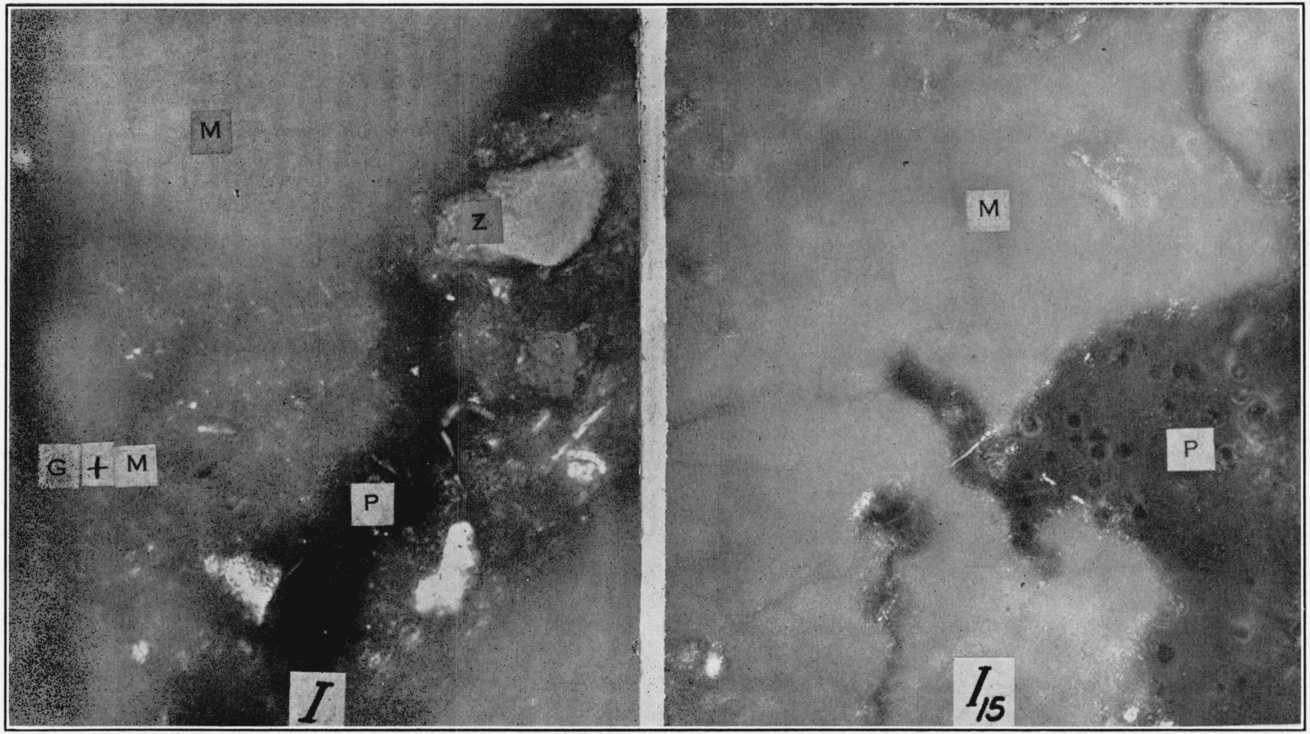

FIGURE 9.—*Sections of firebrick brand I as received (I) and after reheating at 1,500° C (I_{15}) (crossed nicols, ×430).*

The glassy bond plus mullite ($G+M$) with quartz particles (Z) and the mullite (M) in the flint-clay particles are shown in section I. Almost complete absence of quartz and high content of mullite is shown in section I_{15}. Pores are indicated (P).

equivalent of 33 (refractoriness of both aggregate and bonding particles). These facts, together with the high deformation shown by *Q*, indicate that the brick was not well bonded as is supported by figure 8. After reheating at 1,400° C the coarse aggregate shrinks slightly more than the fine, but the latter appeared to have become well bonded. After reheating at 1,500° C the structure was drawn together as a whole; that is, both the aggregate and fines generally shrink together and become well bonded. These changes in structure with reheating can readily account for the greatly reduced deformation after reheating. *Q* is outstanding also in that it has an exceptionally high P_2O_5 content.

Photomicrographs of brand *I*, as received and after reheating, are shown in figures 3, 6, and 9. In figure 3, I_{14} shows a high percentage of coarse aggregate and the shrinkage of the flint-clay particles from the bond clay is pronounced. The aggregate makes a fairly complete skeleton, but there are many pores and the whole has a crumbly and spongy appearance. As might be expected, the deformation is high. *I* in figure 6 was taken with ordinary light and represents the same thin section as *I* in figure 9, except that the latter was taken with crossed nicols. High-glass content in the bond clay and mullite in the flint-clay particle are indicated. Pore space and small quartz crystals may also be seen. I_{15} shows the whole to be a mass of mullite needles, and glass is not much in evidence. As a result the deformation of *I* has greatly decreased.

2. RELATION OF PARTICLE SIZE, RATIO OF FLUX TO SILICA, HEAT TREATMENT, AND DEFORMATION

Figure 10 (lower) shows the total deflection of specimens reheated at 1,400° C and (upper) reheated to 1,500° C as a function of particle size and ratio of flux to silica. In these graphs the highly siliceous bricks appear in the lower left-hand corner and those containing the most alumina appear near the upper right. Although there are some exceptions, the limited number of materials tested do indicate a trend; that is, with increased quantities of coarse aggregate and a high ratio of flux to silica, high deformations are shown. However, after heating at 1,500° C (upper graph) the effect of particle size is apparently eliminated and the value of the ratio of total flux to total silica is the deciding factor as to the extent of the total deformation (coefficient of correlation 0.84) as well as the plastic flow as shown by the data on plastic flow in table 2.

The values for deformation, indicated by length of lines, in the lower graph are averages of all specimens of each brand reheated at 1,400° C; those for 1,500° C are the result of one test only. However, the results of tests for the one specimen (1,400° C reheat) cut from the same brick as that reheated at 1,500° C gives a similar relation. Furthermore, plotting the plastic or residual deformation data in lieu of the total deformation results in a similar type of graph.

Values for deformation obtained for several specimens from the same brand of brick reheated at 1,400° C are given in table 4. The purpose is to show the variation in deformation between specimens of different bricks of the same brand as well as between duplicate specimens of the same brick.

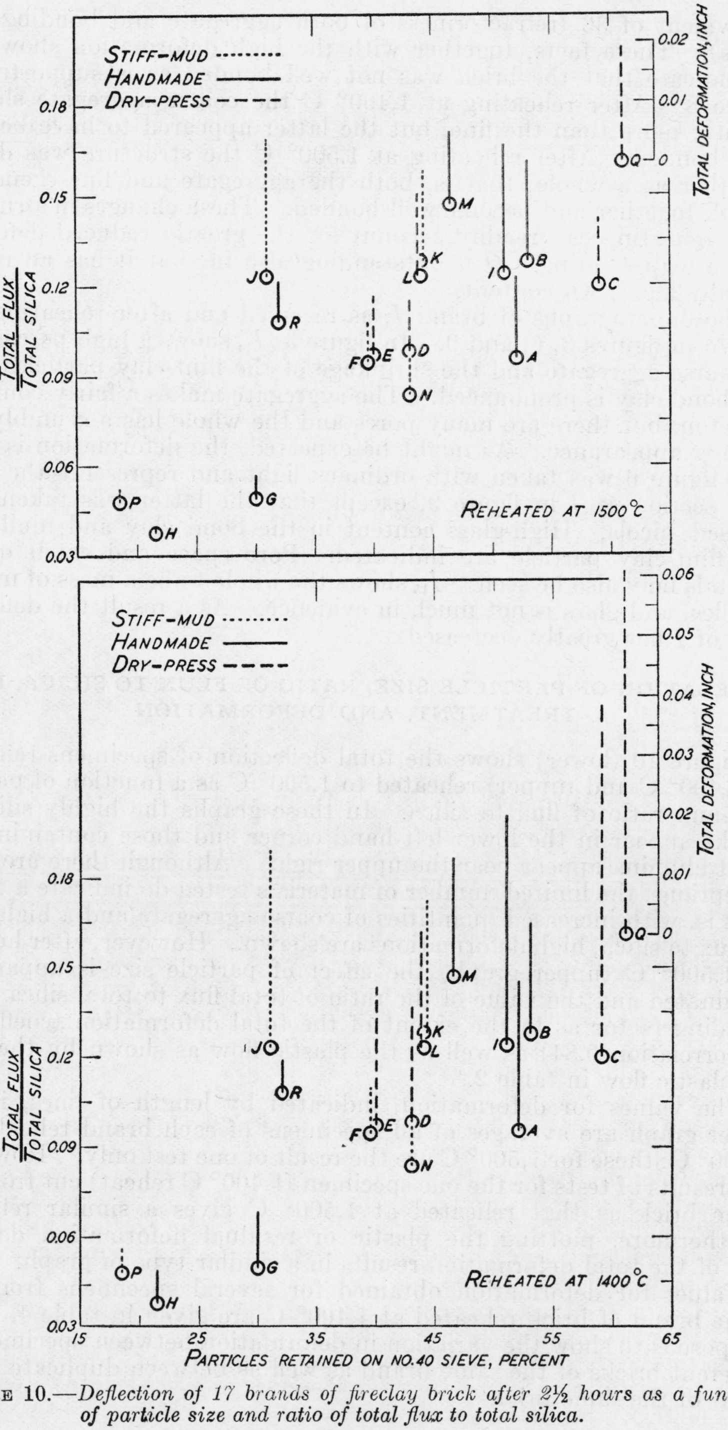

FIGURE 10.—*Deflection of 17 brands of fireclay brick after 2½ hours as a function of particle size and ratio of total flux to total silica.*

The specimens were reheated at 1,400° C and at 1,500° C and tested at 1,220° C. The vertical lines indicating the extent of the deformations may be visualized as perpendicular to the plane of the paper. In the lower graph a trend is indicated, namely deformations increase with quantity of aggregate and increasing ratio of flux to silica. After reheating at 1,500° C the particle size is apparently no longer an important factor in resistance to deformation.

TABLE 4.—*Multiple determinations of total deformation at 1,220° C of fire-clay brick after heating 5 hours at 1,400° C*

[Determinations made at 1,220° C]

Brand and sample [a]	Total deformation after 2½ hr	Brand and sample [a]	Total deformation after 2½ hr	Brand and sample [a]	Total deformation after 2½ hr
	Inch		*Inch*		*Inch*
A1	0.0285	*F1*	0.0095	*M1*	0.0192
A2	.0218	*F2*	.0059	*M2*	.0273
A3	.0250	*F3*	.0075	*M3*	.0122
B1	.0181	*G1*	.0102	*N1*	.0080
B2	.0141	*G2*	.0082	*N2*	.0059
B3	.0225	*G3*	.0101	*N3*	.0067
C1	.0438	*H1*	.0081	*P1*	.0035
C2	[b].0709	*H2*	.0031	*P2*	.0049
				P3	.0036
D1	.0155	*I1*	.0472		
D1	.0142	*I2*	.0346	*Q1*	.0574
D2	.0329	*I3*	.0325	*Q2*	[b].0643
D3	.0146				
		J1	.0360	*R1*	.0537
E1	.0125	*J2*	.0364	*R1*	.0442
E1	.0127	*J3*	.0264	*R2*	.0472
E2	.0236			*R2*	.0513
E2	.0214	*K1*	.0296	*R3*	.0500
E3	.0202	*K2*	.0163	*R3*	.0623
E3	.0227	*K3*	.0206	*R4*	.0517
E4	.0313			*R4*	.0486
E4	.0429	*L1*	.0157	*R5*	.0559
E5	.0241	*L1*	.0269	*R6*	.0548
E6	.0200	*L2*	.0263		
		L3	.0091		

[a] The letter refers to the brand, the number following refers to the specimen. Different numbers indicate specimens were obtained from different bricks of the same brand; duplicate numbers indicate different specimens taken from the same brick.

[b] Specimens failed before 2½-hour period elapsed; value extrapolated.

3. YOUNG'S MODULUS AND STRENGTH

Table 3 gives the modulus of elasticity of fire-clay brick in flexure and the modulus of rupture and porosity for the materials as received and after reheating at 1,400° C. Brands *J* and *Q* as received were tested at 1,150 and 1,100° C, respectively, because, as already stated, they failed shortly after application of the load at 1,250° C. The values represent the average of two or more determinations.

The results show that the modulus of elasticity of most of the bricks is quite low at 1,250° C and for a number of brands is considerably less than 10 percent of the value obtained at room temperature.[16] The highly siliceous type show the least change. The strength values are also appreciably less than those obtained at ordinary temperatures. These low values are evidently due to the partial softening of the glass.

Reheating the specimens at 1,400° C greatly increased both Young's modulus of elasticity and the modulus of rupture. The increase in quantity and size of mullite crystals and decrease in glass, as indicated by the microscopic examinations, is believed to be the major cause for this change.

VI. SUMMARY AND CONCLUSIONS

The total deformations (plastic and elastic) of 17 brands of fire-clay brick in flexure at 1,220° C were determined after reheating at 1,400 and 1,500° C. Similar information was obtained on 8 of the 17 brands

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[16] *Progress report on investigation of fire-clay bricks and the clays used in their preparation.* BS J. Research **3**, 691 (1929) RP 114.

as received from the manufacturer, the remaining 9 having failed before deformation data could be obtained. Young's modulus of elasticity in flexure and the modulus of rupture were determined at approximately 1,250° C on the bricks as received and also after heating at 1,400° C. The deformations were obtained with a stress of approximately 6 lb/in.^{2} applied midspan to a 1- by 1- by 9-inch specimen on an 8-inch span. The modulus of elasticity and strength were determined on the same type of specimen and span; the load increments were varied according to strength of the specimen.

The following results were obtained:

1. The total deformation of specimens heated at 1,400° C increased in general with increase in quantity of particles in the raw brick batches retained on a United States Standard Sieve no. 40.
2. In general, the data indicate that bricks of the dry-press type have uniformly high deformations, the stiff-mud type, with one exception, low deformations, and the handmade type have deformations intermediate of the range of the two other types.
3. Bricks of the lowest ratio of total flux to total silica have much less deformation than those having the highest ratio.
4. The deformation decreased greatly in most cases when the specimens were given preliminary reheat treatments at 1,400 and at 1,500° C. With one exception, the bricks high in silica showed the least change in deformation after the reheat treatments. The petrographic examination showed successive decreases in glass content and increases in the crystallization of mullite with reheating. Specimens showing low deformation when tested as received were either of the siliceous type or contained considerable quantities of mullite crystals. Much glass was present in those showing high deformations.
5. Although there are exceptions, the total deformations of the limited number of materials tested do indicate a trend; that is, deformations increase as the quantity of coarse aggregate and ratio of flux to silica increase. After having been reheated at 1,500° C, particle size is apparently no longer an important factor.
6. Young's modulus of elasticity of specimens in flexure as received from the manufacturer was less than 200,000 lb/in.^{2} for 11 of the 17 specimens. It was about twice as great after reheating at 1,400° C. The strength of the reheated specimens also increased greatly in most cases.

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WASHINGTON, July 13, 1937.

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