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YOUNG'S MODULUS OF ELASTICITY, STRENGTH, AND EXTENSIBILITY OF REFRACTORIES IN TENSION

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ABSTRACT

Young's modulus of elasticity, strength, and extensibility were determined at ordinary temperatures upon the following materials in tension: 16 brands of fire-clay brick with a wide range in silica content, representing the stiff-mud, dry-press, and handmade methods of forming; one brand each of silica brick, chrome, forsterite, 60 percent alumina, 80 percent alumina, and of mullite. A comparison is made of the tensile properties of specimens obtained parallel to the 9-in. dimension with those obtained parallel to the 4½ in. dimension. The effects of method of setting the bricks in the kiln during firing, load during firing, and weight of the brick on the tensile properties of fire-clay brick made by the dry-press process were briefly studied. With one exception, the tendency is quite general for the tensile properties to vary greatly not only between units but also within the unit.

CONTENTS

I. INTRODUCTION

The brittleness of refractory products has in the past been a serious handicap to the study of their tensile properties. Within recent years the development of the optical strain gage for measuring minute length changes has given the research worker a tool which has eliminated most of the difficulties encountered in such a study, so that strain measurements of all types of refractory materials can now be made with reasonable accuracy.

Although refractories are ordinarily subjected to comparatively small external loads, more information on their little-known structural properties may lead to a better understanding of their behavior in certain types of service. A knowledge of the tensile properties of fired refractory products is desirable because of the trend toward fairly large shapes in hanging roofs designed for modern high-power boiler settings, heat treating and other furnaces. Also, there is often a decided lack of agreement in the results of certain tests of apparently duplicate samples of refractory bricks.

A study was therefore undertaken to make information available on the tensile properties of the standard 9-inch-size firebrick and also to determine the extent of the variation in these properties within the brick and between bricks. This shape is produced in largest quantities, is readily obtainable, enables a selection representative of the different localities and processes of manufacture, different degrees of heating, and different methods of setting in the kiln. The specimens used for study were machined from sections, the axes of which were initially lengthwise or crosswise to the brick. Measurements were made of the ultimate stress, Young's modulus and maximum strain or extensibility of the specimens tested in tension at room temperature.

II. MATERIALS

Sixteen brands of fire-clay bricks, and one brand each of silica, chrome, forsterite, 60 percent alumina, 80 percent alumina, and a specially prepared shape of mullite (cylinders 9½ in. long and 2½ in. in diam) were obtained from 10 manufacturers in different locations in the United States. Seven of the 16 brands of fire-clay bricks were formed by the dry-press, 5 by the stiff-mud, and 4 by the handmade process.

1. CHEMICAL ANALYSES [1]

The chemical compositions of the fire-clay bricks are given in table 1. The method of analysis followed was, in general, that described by Lundell and Hoffman [2] for refractories.

The compositions show the wide range in silica, alumina, and flux contents of the materials. The silica ranges from 14.9 percent in the high-alumina brick to 96 percent in the silica brick. In the fire-clay brick the silica ranges from 47.8 to 80.7 percent. The flux ranges from 3.2 to 7.8 percent.

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[1] Made by E. H. Hamilton of the Bureau staff.

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

TABLE 1.—*Tensile and other properties of firebrick* [a]

Brand [b]	Method of manufacture [c]	Pce	Porosity	Chemical composition					Young's modulus of elasticity			Strength			Extensibility			
				SiO_2	Al_2O_3	Total flux	$Fe_2O_3+TiO_2$	P_2O_5	Lengthwise	Crosswise	All specimens	Lengthwise	Crosswise	All specimens	Length wise	Crosswise	All specimens	Coefficient of variation [f]
		Cone	%	%	%	%	%	%	1,000 lb/in.²	1,000 lb/in.²	1,000 lb/in.²	lb/in.²	lb/in.²	lb/in.²	%	%	%	%
1	DP	34	16.2	47.8	44.4	7.8	3.1	1.06	1,885	2,200	1,990	385	290	355	0.0205	0.0135	0.0185	4.2
2	DP	33-34	21.1	53.9	40.2	5.9	3.7	.11	1,190	1,285	1,225	275	240	265	.0230	.0190	.0225	26.0
2 [d]	DP								960	1,145	1,025	245	185	225	.0255	.0165	.0225	10.2
3L [e]	DP	33	17.8	51.5	41.2	7.3	4.2	.08	1,530	2,530	1,860	355	350	355	.0235	.0140	.0200	2.9
3H [e]	DP	33	17.6	51.6	40.7	7.7	4.5	.09	2,160	3,400	2,575	430	465	440	.0200	.0135	.0180	11.2
4	HM	33	25.8	50.8	42.7	6.7	4.4	.18	545	670	585	125	90	115	.0240	.0140	.0205	31.0
5	DP	32-33	20.7	50.9	42.0	7.2	4.7	.16	735	1,120	865	180	195	185	.0250	.0185	.0230	18.0
6	SM	32-33	21.5	52.0	41.2	6.8	4.4	.18	1,465	1,655	1,525	335	235	305	.0230	.0150	.0205	12.9
6 [d]	SM								1,685	1,950	1,775	360	335	350	.0215	.0170	.0200	10.5
7	HM	32	25.1	58.5	34.8	6.7	4.1	.09	1,415	1,545	1,460	325	265	305	.0235	.0170	.0210	2.2
7 [d]									1,735	1,450	1,640	335	235	300	.0195	.0165	.0185	25.5
8	SM	31	21.8	56.2	37.0	6.8	4.3	.09	1,560	1,515	1,545	365	325	350	.0235	.0220	.0230	11.7
8 [d]									1,265	1,170	1,235	305	260	290	.0245	.0220	.0235	16.9
9	DP	33	23.3	54.2	39.5	6.4	4.5	.11	1,960	2,320	2,080	430	385	415	.0220	.0170	.0205	8.7
10	SM	32-33	22.9	53.5	40.2	6.4	4.6	.10	3,865	2,465	3,400	555	415	510	.0145	.0170	.0155	9.6
11	DP	32-33	18.7	56.9	37.8	5.3	2.5	.52	595	525	575	165	150	160	.0275	.0285	.0280	20.0
12	SM	32.33	8.9	59.0	36.5	4.6	2.9	.13	5,500	4,760	5,255	755	370	630	.0140	.0090	.0120	50.2
13	HM	32-33	22.0	59.1	36.0	4.9	3.0	.12	2,440	2,500	2,460	405	490	435	.0165	.0200	.0175	11.5
14	DP	31-32	23.2	58.1	34.5	7.4	4.9	.11	1,855	2,205	1,970	375	395	385	.0205	.0185	.0200	15.2
15	SM	31-32	25.4	65.3	29.4	5.3	3.5	.08	2,130	1,875	2,045	470	230	390	.0220	.0130	.0190	11.7
15 [d]	SM								2,135	1,510	1,925	425	295	370	.0205	.0195	.0200	8.5
16	HM	29-30	29.9	80.7	16.1	3.2	2.4	.07	490	565	515	175	180	180	.0365	.0330	.0355	19.4
17	HM	32-33	29.3	96.0					470	505	485	200	275	225	.0420	.0550	.0465	14.8
18	DP	35	19.8	36.8	55.7	7.4	3.8	.36	3,235	3,405	3,300	660	560	620	.0205	.0165	.0190	33.0
19	DP		26.8	14.9	79.3	5.7	4.1	.39	4,680	5,475	4,950	1,055	895	1,005	.0225	.0165	.0205	4.6
20			26.6						3,025	4,190	3,415	555	565	555	.0185	.0140	.0170	9.4
21	DP		24.3						1,000	1,050	1,015	235	225	230	.0235	.0215	.0230	7.4

[a] Values of tensile properties represent average values for 3 bricks.

[b] Brands 1 to 16 are fire-clay brick, 18 and 19 high-alumina, and 17, 20, and 21 are silica, chrome, and forsterite, respectively. Information on the mullite refractory is given in table 3.

[c] DP, dry press; HM, handmade; SM, stiff-mud.

[d] Represent duplicate samples.

[e] 3L and 3H same brand of brick, but fired at cones 12 and 14, respectively.

[f] The two lengthwise specimens from each brick were taken as the unit for the sample.

2. PYROMETRIC-CONE EQUIVALENTS

The pyrometric-cone equivalents (pce or softening points) were determined according to the ASTM standard method, serial designation C 24–33.[3] The values, given in table 1, ranged from 29–30 to 35. None of the pce values of the so-called special type of refractories are included except that of the 60 percent of alumina brick.

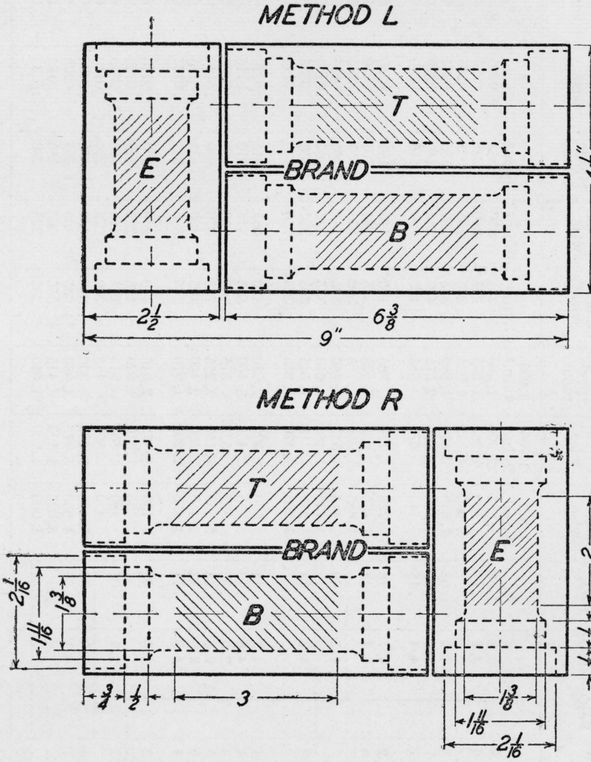

FIGURE 1.—*Sections of the brick from which specimens were prepared*

In each sample of three bricks two were cut by method L and one by method R.

3. POROSITY

The porosity determinations were made as follows: three cylindrical specimens,[4] approximately 2¾ in. long and 1⅜ in. in diam, prepared from three different bricks of each brand, were saturated by boiling in water for 1½ hr under a pressure of 4 mm of mercury. The specimens remained under water and under pressure which gradually increased to atmospheric overnight. They were then weighed. The porosity, recorded in percent, is the ratio of the volume of water absorbed to the bulk volume of the specimen. The porosities (table 1) range from 8.9 percent for a stiff-mud fire-clay brick to 29.9 percent for a highly siliceous fire-clay brick.

The chemical analysis, pyrometric-cone equivalent, and porosity are given merely for descriptive purposes and no attempt is made to correlate these properties with the tensile properties.

[3] American Society for Testing Materials Book of Standards for 1933, pt. 2, p. 184.
[4] Cut from ruptured tensile-test specimens.

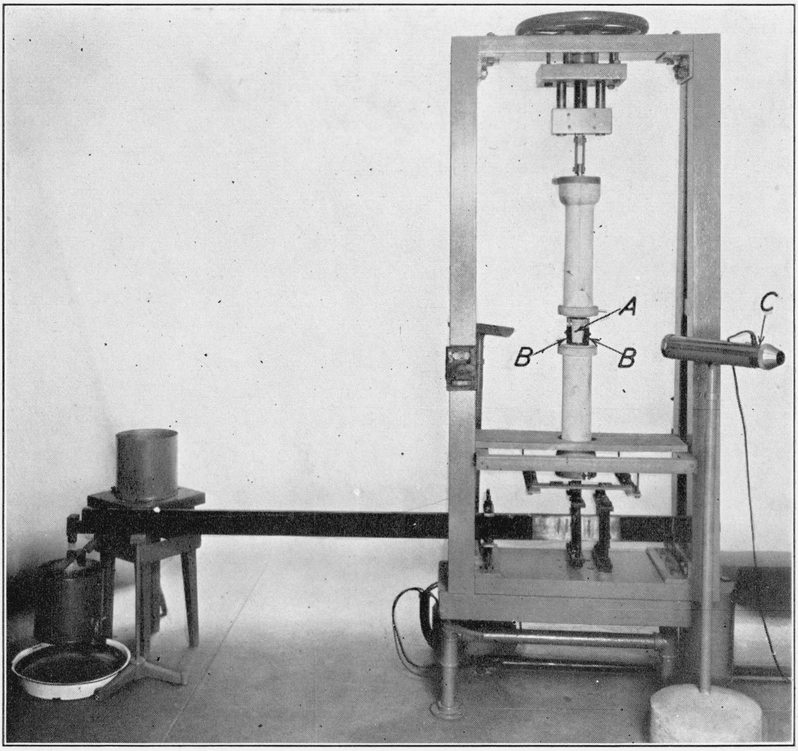

FIGURE 2.—*Apparatus for obtaining tensile properties of refractory materials.*

Specimen A, with strain gages B attached, and the autocollimator C are all in position for making observations.

III. SPECIMENS AND APPARATUS

1. SPECIMENS

Cylindrical test specimens with shoulders and flanges, as shown in figure 1, were ground to size on a small lathe from sections cut from individual bricks. The crosswise specimen (marked E) could be taken from the end to the left or to the right of the brand name.

2. DESCRIPTION OF APPARATUS

Figure 2 shows the testing machine for making the tensile tests with the optical strain gage of the Tuckerman type[5] attached to a specimen and the autocollimator in position for an observation. The testing machine is of the counterbalanced simple beam type with the fulcrums spaced to give a 20:1 ratio at the straining clevis. Fulcrum plates of the A. H. Emery type are provided in place of knife edges to insure constancy of the lever ratio. The load is obtained by means of no. 12 lead shot flowing into a container at one end of the beam at a rate to cause a load increase of 290 lb/min. The flow of shot is controlled by means of valves actuated by solenoids.

Figure 3 shows the assembly of the specimen and strain gages, upper and lower specimen holders or grips[6] and aligning bearings. All bearing surfaces of grips and specimens are ground parallel to insure their proper alignment. The two strain gages are mounted diametrically opposite as indicated. To avoid shifting of the lozenge on the irregular

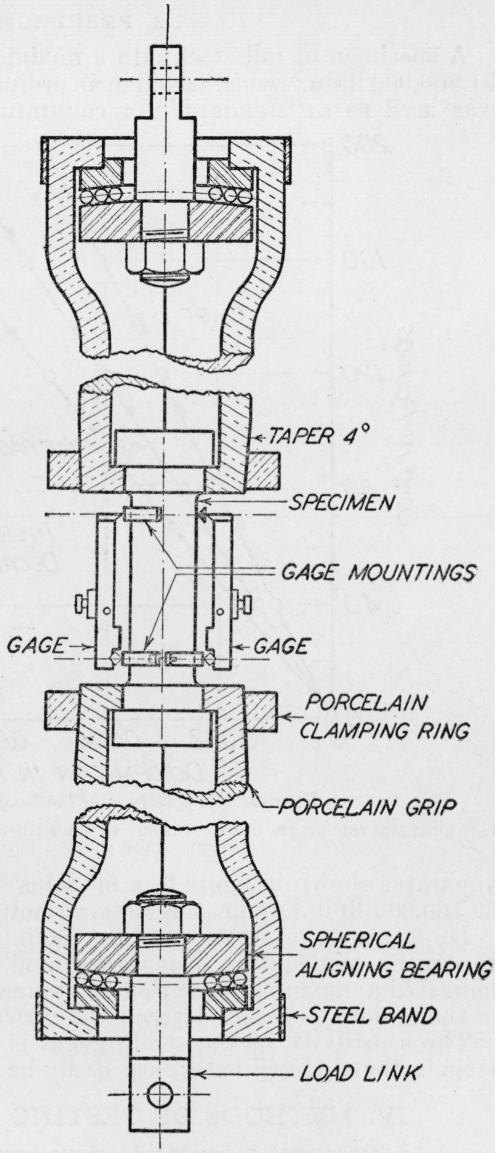

FIGURE 3.—*Assembly of the specimen, strain gages, gage mountings, porcelain specimen grips, and aligning bearings.*

[5] *Optical strain gages and extensometers.* Proc. Am. Soc. Testing Materials 23, pt. II, p. 602 (1923).

[6] Porcelain holders or grips were made and used because plans have been made to study tensile properties of refractories at elevated temperatures.

surface of the specimen as well as to avoid injuring the knife edge and lozenge of the gages by abrasive contact with the specimen, they are rested on metallic rings attached to the specimen. Each ring or gage mounting contacts the specimen at four points approximately equally spaced around the circumference. Tests with and without rings indicated that the rings did not affect the results.

3. PRECISION

A specimen of rail steel with a modulus of elasticity in tension of 31,800,000 lb/in.[2] (when tested in an ordinary type of testing machine), was used as a "standard" for calibrating the machine. With the

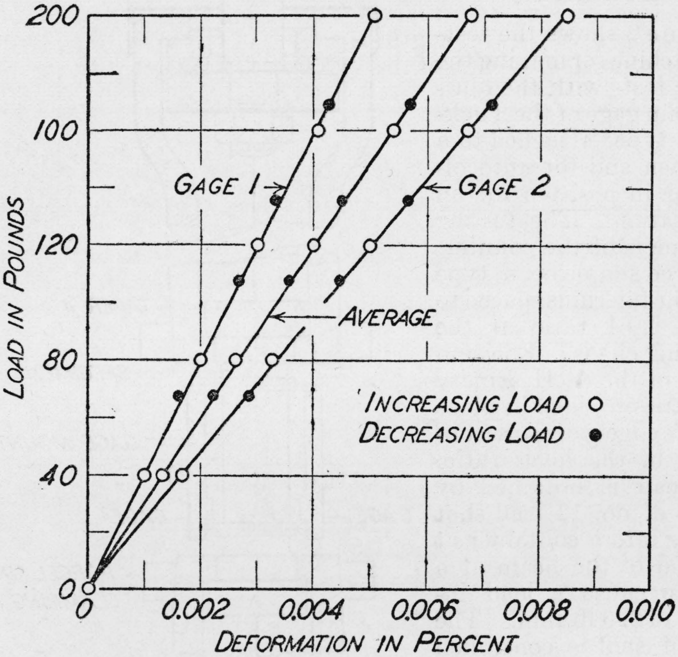

FIGURE 4.—*One type of load-deformation curve.*

Individual gage readings are shown. The stress-strain relation obtained during loading of the specimen is the same as that obtained during unloading.

apparatus shown in figure 2, a modulus of elasticity was obtained of 32,100,000 lb/in.[2], indicating an accuracy of about 1 percent.

Duplicate determinations of the modulus of elasticity of refractory specimens made after dismantling and reassembling of the setup indicated a maximum variation of 3 percent. However, the variation in the majority of such determinations was less than 2 percent.

The sensitivity of the strain gages is 0.000002 in., to which the scale in the autocollimator may easily be read.

IV. METHODS OF TESTING AND SAMPLING

1. YOUNG'S MODULUS OF ELASTICITY IN TENSION

(a) LENGTHS AND POSITIONS OF STRAIN GAGES

After the specimen was placed in the holders preparatory to testing, two strain gages of the desired length were attached. The gage length was 2 in., but extensions were provided to accommodate specimen gage lengths of 3 and 6 in. Two gages were used in order to obtain an average deformation. Inasmuch as the center of a brick is usually softer than the outside, some differences could be expected in deformation readings obtained by the two gages. No readings were taken for at least 15 min after placement because of the sensitiveness of the gages to body temperature. Observations were made to determine if the gages had become stabilized before loads were applied. The strain was increased in the specimens in five nearly equal increments up to a total of approximately 0.01 percent.

(b) STRESS-STRAIN CURVES

One type of load-deformation curve for a specimen of fire-clay brick, using a 3-in. gage length, is shown in figure 4. The individual values obtained with each of the two gages, together with the average

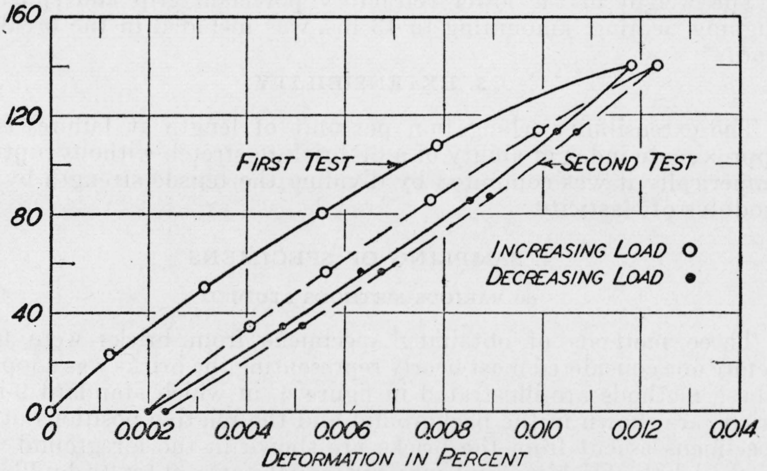

FIGURE 5.—*A second type of load-deformation curve.*

The mean reading of the two gages is shown. The stress-strain relation during unloading of the specimen is not the same as that obtained during loading. A permanent set of the specimen is indicated after each of the two tests.

values, are shown. In this case the variation in deformation indicated by the two gages, based on the average values, was 50 percent.[7] This type of curve illustrates a case in which the deformation values obtained with decreasing loads are, within experimental error, the same as those obtained with increasing loads.

Figure 5 shows a second type of load-deformation curve where the deformation values obtained with decreasing loads are not the same as those obtained with increasing loads and indicate that there was permanent elongation of the specimen. The value of each point is

[7] The deformations of six specimens from two bricks were obtained by placing the two available strain gages successively at four pairs of different positions of approximately equal spacing around each specimen using individual protective mountings for the gages. This was done to determine how uniformly any two positions of the gages diametrically opposite would yield the same average deformation as any other two diametrically opposite gages. The maximum variation based on the average deformation ranged from 1.5 to 5 percent for 20 pairs of values (4 pairs for each of 5 specimens) and 11.7 percent for the 4 pairs of readings for the sixth specimen. Some of the variation may be accounted for by the change in modulus of elasticity of the material between loadings. The extreme variation of 11.7 percent is so far out of line from the other 23 values that it seems probable it is in error.

If the extreme individual values for the specimen which showed the greatest differences are considered without regard to whether or not gages were diametrically opposite, the greatest variation based on the average was 72 percent and the specimen which showed the least difference for all eight readings showed a variation of 13.5 percent.

the average reading of the two gages. The modulus of elasticity was computed from the line resulting from the average of the load-deformation curves obtained during a second test, also shown in figure 5 (average line not shown) by the usual stress-strain formula, namely:

$$\text{Young's modulus} = \frac{\text{stress}}{\text{strain}} = \frac{\text{load}}{\text{deformation per unit of length X area}}.$$

2. TENSILE STRENGTH

The same specimens on which the elasticity had been determined were in general used for tensile-strength determinations. After the elasticity measurements had been obtained, the strain gages were removed and the flow of shot continued until the specimen ruptured.

The weight of the lower refractory porcelain grip and spherical aligning bearing, amounting to 13 lbs, was included in the breaking load.

3. EXTENSIBILITY

The extensibility (elongation per unit of length at failure) is an approximate index of ability of a firebrick to stretch without rupture; numerically it was computed by dividing the tensile strength by the modulus of elasticity.

4. SAMPLING OF SPECIMENS

(a) VARIOUS METHODS STUDIED

Three methods of obtaining specimens from bricks were tried before one considered most nearly representing the bricks was adopted. These methods are illustrated in figure 6, in which standard 9-inch bricks are shown in the background and the relative positions of the specimens as cut from the bricks are shown in the foreground. In method I the brick was cut into two equal parts (9 by 2¼ by 2½ in.) parallel to the 9 in. dimension, one part (F) was prepared to accommodate a 6-in. gage length and the other (G) to accommodate a 2-in. gage length in the central portion of the specimen and a specimen on either end (A, H) for tensile-strength tests only. In method II the brick was cut into four equal portions (M, L, K, and J) parallel to the 4½-in. dimension and finished to accommodate 2-in. gage lengths. In method III the two specimens (T, B) with an over-all length of 6⅜ in. were prepared from portions of the brick cut parallel to the 9 in. dimension and one specimen (E) from a section cut parallel to the 4½ in. dimension.

Results of tests of specimens prepared by the three different methods of sampling are given in table 2. The first three groups of specimens are from bricks made by manufacturer X by three different processes. The comparisons of tensile properties between bricks are of uncertain value because one brick only was sampled by each method. However, the three methods of specimen sampling illustrate effectively the impossibility of cutting a simple specimen from any one portion of the brick which can be considered as representative. For example, in the first group of bricks, manufactured by the handmade process, the modulus of elasticity of specimen G was 59 percent greater than that of F and the tensile strength was about 120 percent greater.

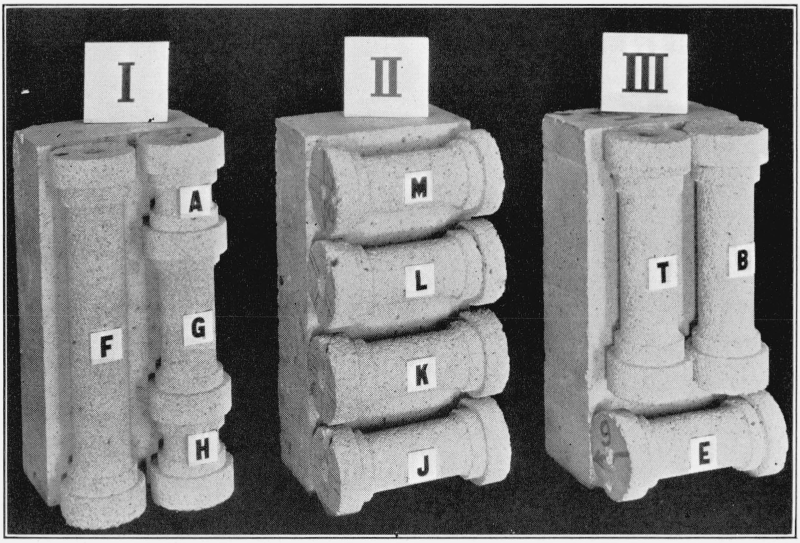

FIGURE 6.—*Different types of test specimens and the methods by which they were laid out.*

Method III was adopted because it was considered the specimens were more nearly representative of the brick.

The tensile-strength determinations of specimens A, G, and H serve to illustrate the variability along the longitudinal half of the brick. In the case of the four lateral specimens, illustrated by method II, the highest value of the modulus of elasticity (brick 2, table 2) is about 40 percent above that of the lowest value. Both the elasticity and strength of this brick indicate considerable difference in structure between one end of the brick and the other. The average value for the specimens from brick 1 and that for brick 2 indicate the probability of some difference in their treatment during manufacture. The specimens in brick 3 combined methods of sampling I and II, as shown in figure 6, III. In this case the mean Young's modulus of the two lengthwise specimens was about 50 percent greater than that of the crosswise specimen. The two lengthwise specimens are in excellent agreement. Considering the nine specimens of all three bricks the mean elasticity value for the four specimens sampled lengthwise was in good agreement with the mean of the five specimens sampled crosswise.

TABLE 2.—*Tensile properties of fire-clay brick sampled by different methods*

Manufacturer	Method of manufacture	Brick no.	Specimen [1]	Modulus of elasticity	Strength	Extensibility	Maximum [2] extensibility variation in each brick
				1,000 lb/in.²	lb/in.²	%	%
		1	F	1,410	180	0.0130	32.2
			G	2,240	405	.0180	
			H	--------	370	--------	--------
			A	--------	255	--------	--------
		2	J	2,380	295	.0125	17.0
			K	2,760	340	.0125	
			L	3,300	350	.0105	
X	Handmade		M	3,270	410	.0125	
		3	T	3,500	620	.0175	2.8
			B	3,430	625	.0180	
			E	2,200	440	.0200	--------
			Lengthwise avg	2,645	460	.0165	--------
			Crosswise avg	2,780	365	.0135	--------
		4	F	1,305	385	.0295	26.9
			G	1,625	365	.0225	
			H	--------	435	--------	--------
			A	--------	480	--------	--------
		5	J	1,260	280	.0225	30.1
			K	1,495	300	.0200	
X	Dry Press		L	1,990	330	.0165	
			M	1,725	350	.0205	
		6	T	1,330	390	.0295	20.6
			B	1,600	380	.0240	
			E	930	255	.0275	--------
			Lengthwise avg	1,465	380	.0265	--------
			Crosswise avg	1,480	305	.0215	--------
		7	F	3,110	540	.0175	22.9
			G	3,620	800	.0220	
			H	--------	495	--------	--------
X	Stiff mud		A	--------	660	--------	--------
		8	J	2,010	370	.0185	13.0
			K	--------	--------	--------	
			L	395	85	.0210	
			M	2,710	505	.0185	

[1] Key letter of specimen corresponds to that shown in figure 6.
[2] Specimen E not included in determining the spread.

TABLE 2.—*Tensile properties of fire-clay brick sampled by different methods*—Con.

Manufacturer	Method of manufacture	Brick no.	Specimen	Modulus of elasticity	Strength	Extensibility	Maximum extensibility variation in each brick
				1,000 lb./in.	lb./in.²	%	%
X	Stiff mud	9	T	3,220	325	.0100	10.5
			B	3,630	650	.0180	
			E	2,690	350	.0130	
			Lengthwise avg	3,395	580	.0170	
			Crosswise avg	1,950	320	.0180	
Y	Dry press	10	F	1,120	160	.0140	42.3
			G	1,380	295	.0215	
			H		410		
			A		385		
		11	J	5,100	435	.0085	32.3
			K	4,720	335	.0070	
			L	4,150	365	.0090	
			M	5,450	355	.0065	
		12	T	2,610	505	.0195	13.4
			B	2,960	500	.0170	
			E	3,760	340	.0090	
			Lengthwise avg	2,035	365	.0180	
			Crosswise avg	4,635	365	.0080	
Z	Dry press	13	F	320	75	.0230	23.1
			G	380	110	.0290	
			H		95		
			A		100		
		14	J	880	125	.0140	43.0
			K	1,030	125	.0120	
			L	1,060	190	.0180	
			M	905	190	.0210	
			Lengthwise avg	350	90	.0260	
			Crosswise avg	970	155	.0160	

Specimens from bricks 4, 5, and 6, made by the dry-press process, do not show a variation in values between bricks as great as was shown in bricks 1, 2, and 3. The variation within an individual brick was about the same in magnitude as in bricks 1, 2, and 3 of the first group. The mean modulus values for the specimens cut lengthwise to the brick are approximately equal to the mean values of those cut crosswise.

Specimens cut from bricks 7, 8, and 9, manufactured by the stiff-mud process, showed greater variations between bricks. Variation in values was especially evident in specimens sampled in accordance with method II, figure 6. The two specimens from the central portion of the brick were unsatisfactory because of laminations. As indicated in the table, K broke before any data were obtained and specimen L had unusually low tensile properties caused by laminations.

There is an unusually wide range in tensile properties between bricks 10, 11, and 12, made by manufacturer Y by the dry-press method, due possibly to differences in kiln temperature during manufacture. On the other hand, variations in the modulus of elasticity within the brick are not as wide as in some of the other brands.

Specimens from bricks 13 and 14, also of the dry-press variety but made by manufacturer Z, gave the lowest tensile strength and modulus of elasticity of those recorded in this table. Variation between bricks was again high, but the values obtained with test specimens cut in the same manner were quite uniform.

The range in extensibility of all specimens recorded in table 2 is from 0.0065 percent to 0.0295 percent. The greatest range (0.0065 to 0.0215 percent) in any one group is represented by bricks 10, 11, and 12. These data illustrate the very wide range existing in this important property between bricks made by different manufacturers, bricks made by the same manufacturer but by different processes, and bricks made by any one manufacturer and one process of manufacture.

(b) VARIATION IN MODULUS OF ELASTICITY OVER 6-INCH GAGE LENGTHS

Four specimens from three brands of bricks and three specimens of a mullite refractory were prepared to accommodate 6-in. gage lengths (see specimen F, fig. 6). Table 3 gives Young's modulus in tension for the three 2-in. gage lengths making up the 6-in. gage length. In addition, Young's modulus and tensile strength are given for the 6-in. gage length of the specimens. These data illustrate the variability in tensile properties of bricks which may exist along the longitudinal axis and that the modulus of elasticity taken over the 6-in. length is very nearly the same as the mean of the three 2-in. gage lengths.

TABLE 3.—*Young's modulus of elasticity of firebrick in tension*

[Comparison of 2-in. and 6-in. gage lengths of the same specimen]

Manufacturer [a]	Method of manufacture	Modulus of elasticity				Strength [c]
		2-in. gage length			6-in. gage length	
		Bottom	Middle	Top		
		1,000 lb/in.²	1,000 lb/in.²	1,000 lb/in.²	1,000 lb/in.²	lb/in.²
X	Dry-press	1, 210	1, 340	1, 410	1, 305	385
X	Stiff-mud	3, 670	3, 230	2, 560	3, 110	540
X	do	2, 560	3, 490	3, 490	3, 050	460
Z	Dry-press	295	390	380	320	75
W [b]		6, 720	6, 350	6, 950	6, 720	665
W		6, 700	6, 950	7, 050	6, 950	1, 115
W		6, 220	6, 570	6, 570	6, 330	855

[a] X and Z, fire-clay brick: W, mullite refractory.
[b] Samples submitted were cylinders 9½ in. long and 2½ in. in diameter.
[c] Determined after modulus of elasticity data for 6-in. specimen had been obtained.

(c) VARIATION IN MODULUS OF ELASTICITY WITH CHANGE IN CROSS SECTION OF SPECIMEN

A few tests were made to determine the effect on the modulus of elasticity of changing the diameter of the specimen. For this purpose three brands of bricks were used, the specimens in two cases were prepared to accommodate 6-in. gage lengths and one for a 3-in. gage length. In the former case the specimens were tested with three different cross-sectional areas, of approximately 1.75, 1.50, and 1.10 in.², respectively, and in the latter with cross-sectional areas of 1.50 and 1.10 in.², respectively. The Young's moduli of these specimens were measured in tension without rupturing the specimens in order to permit retesting. After the first test these specimens were machined to the next smaller size and again tested and the same procedure followed for the third test for specimens of brands 2 and 8.

The results are given in table 4. The spread between the maximum and minimum values for the different cross-sectional areas was considered reasonable.

TABLE 4.—*Young's modulus of elasticity of firebrick in tension*

[Comparison of values for specimens of different cross sections]

Brand	Method of manufacture	Gage length	Cross-sectional area	Modulus of elasticity	Spread
		in.	in.²	1,000 lb/in.²	%
2	Dry-press	6	1.77 1.50 1.12	1,250 1,255 1,260	0.8
8	Stiff-mud, repress	6	1.75 1.49 1.12	1,220 1,180 1,145	6.3
12	Stiff-mud	3	1.49 1.11	7,080 7,100	.3

(d) METHOD OF SAMPLING SPECIMENS ADOPTED

The method of sampling designated III (fig. 6) was adopted because it would give a measure of the tensile properties of specimens prepared from sections cut crosswise and lengthwise to the brick. The over-all length of specimens was either 4½ or 6⅜ in., suitable for 2-in. and 3-in. gage lengths, respectively. The diameter of the flanges was 2¹⁄₁₆ in. and that of the cylinder 1⅜ in., the latter with a cross-sectional area of about 1.50 in.²

The final tests were made on nine specimens from three bricks; in two bricks the crosswise specimens were cut from the end to the left of the brand name (method L) and in the third brick from the end to the right of the brand name (method R), figure 1. It is possible that the top and bottom faces during forming and repressing are not always in the same relative order with respect to brand name. This applies especially to bricks formed by the handmade process, where the brick is stamped during repressing.

For the purpose of this investigation the cross-sectional area of about 1.50 in.² was adopted for the test specimens. This was, on the one hand, small enough to avoid breaking the grips and to secure flanges as large as possible for good seating of the specimens in the grips, and on the other hand, was as large as possible in order to obtain a representative volume of material within the gage length.

V. RESULTS AND DISCUSSION

1. COMPARISON OF TENSILE PROPERTIES WITHIN THE BRICK, BETWEEN BRICKS, AND BETWEEN BRANDS

Process of forming, temperature of firing during manufacture, method of kiln setting, particle size, and composition affect the properties. With the exception of particle size, some discussion will follow relative to the apparent effects of each of these variables on the tensile properties. Data were obtained in only one case (brand 3) on the influence of firing temperature on the tensile properties, but that example shows that firing temperature is an important factor in the magnitude of the variation of the tensile properties.

Table 1 gives the average modulus of elasticity, tensile strength and extensibility of 3 bricks taken from each of 21 brands. The columns headed "lengthwise" give values from data obtained on six specimens and those headed "crosswise", values on three specimens. A third column headed "all specimens" gives the mean value of all nine specimens machined from the three bricks.

The group of three brands, 4, 5, and 6, represents one manufacturer's products, each formed by a different process. The group, brands 11, 12, and 13, represents a second manufacturer's products, each also formed by a different process. In the first group, stiff-mud brick had the highest modulus of elasticity and strength and the handmade, the lowest. However, the extensibility of the dry-press bricks (brand 5) exceeded appreciably that obtained on bricks made by the other two processes. This was true for specimens cut either lengthwise or crosswise. For brands 11, 12, and 13, the stiff-mud brick also had the highest modulus of elasticity and strength, but these properties were lowest for the dry-pressed bricks. The brick formed by the dry-press process (brand 11) also gave the greatest extensibility, much greater, in fact, than that of either brand 12 or 13. The extensibility of the crosswise specimen of brand 12 was exceptionally low, far lower than that of any other brand. In brands 9 and 10, a third manufacturer's products, the modulus of elasticity of the lengthwise specimens of the stiff-mud brick was about double that of the dry-press brick. However, the values of the crosswise specimens were not appreciably different in either modulus of elasticity or tensile strength. When the mean of all specimens is considered, the bricks made by the dry-press method were decidedly higher in extensibility than those made by the stiff-mud process. Brands 14, 15, and 15c, from another manufacturer, showed comparatively little difference in tensile properties regardless of method of manufacture; the only exception was shown by the crosswise specimen of the stiff-mud product. The combined average values for both samples of brand 7 and for both samples of brand 8, handmade and stiff-mud bricks of still another manufacturer, illustrate that a lower modulus of elasticity and higher strength may be obtained by the latter process of forming. The extensibility of the handmade (brand 7) is lower than that of the stiff-mud brick, although the reverse might be expected.[8]

Brand 16 is a highly siliceous fire-clay brick of low modulus of elasticity and low tensile strength. The ratio of strength to modulus of elasticity is high, resulting in high extensibility, a very favorable property in firebrick.

The change in tensile properties caused by a difference in firing temperature of approximately 80° C is illustrated by brand 3L (fired at cone 12) and 3H (fired at cone 14). Young's modulus and also the strength were decidedly greater for 3H than 3L, although the modulus increased much more than the strength and consequently resulted in a lower extensibility.

Brand 17, a silica brick (96 percent of silica), has a low modulus of elasticity and good strength, resulting in an unusually high extensibility for refractory brick. Brand 16, containing the next highest percentage of silica (80.6 percent), had the next highest extensibility,

[8] J. Am. Ceram. Soc. **16**, 11 (1933). An adjustment of the particle sizes or of the composition might possibly overcome this condition.

much higher than that of the other brands (excepting the silica brick) tested. Brands 18 and 19 are high-alumina refractories. The modulus and strength of brand 18 are substantially uniform, irrespective of direction in which specimens were taken. Even though Young's modulus of brand 19 is high, the extensibility compares favorably with that of the other brands of dry-press brick. Brand 20, a chrome brick, showed exceptional differences in Young's modulus between lengthwise and crosswise specimens, corresponding in this respect to brands 3 and 10. Brand 21, a forsterite brick, on the other hand showed exceptional agreement in Young's modulus as well as strength between lengthwise and crosswise specimens, and in this respect corresponds to brands 8, 11, and 16.

Duplicate sets of nine specimens from three bricks each of brands 2, 6, 7, 8, and 15 were tested and the results are given in table 1. Although values of modulus of elasticity and strength in individual instances show some variation between the original and the duplicate series of test specimens, results in general are satisfactory, especially in view of the inherent variability of firebrick. The mean extensibility (considered the important tensile property from the spalling viewpoint), was in unusually good agreement in each case excepting brand 7, between the first and second lots of bricks tested.

Based on strength and Young's modulus of elasticity of firebrick in tension for the brick sampled both lengthwise and crosswise, the results given in table 1 show that the bricks may be generally classified into the three following types:

1. These properties are approximately alike irrespective of the direction of sampling. Handmade brands are of this type.
2. These properties of the lengthwise specimens are greater than those of the crosswise specimens. The stiff-mud brands are of this type.
3. The moduli of elasticity of the crosswise specimens are greater than of the lengthwise specimens and the strengths are approximately equal. Most of the dry-press brands are of this type.

The results, in general, also show that the dry-press bricks had the greatest extensibility, but that the two handmade brands of highest silica content had outstandingly high extensibilities.

The range in mean extensibilities for the different brands was from 0.0120 to 0.0465 percent, but the great majority of brands were grouped in the comparatively narrow range from 0.0175 to 0.0235 percent. Figure 7 shows the relation of extensibility between lengthwise and crosswise specimens plotted in the order of decreasing extensibility of the lengthwise specimens. The tendency of the crosswise specimens to exhibit a generally lower extensibility than the lengthwise specimen is clearly illustrated.

The coefficient of variation [9] for the lengthwise extensibility of bricks was computed for each brand. The values ranged from 2.2 to 50.2 percent, table 1. When grouped according to method of forming, the mean coefficient for those made by the dry-press process was 13.1 percent, the stiff-mud 16.5 percent, and the handmade 20.4 percent. If brand 12 (badly laminated), which had an exceptional coefficient of variation, is eliminated from the stiff-mud group,

[9] Manual for interpretation of refractory test data. ASTM Standards on Refractory Materials (Feb. 1935). Applying the formulas given to samples of only three bricks, as was done in this study, yielded coefficients of variation which are unduly large.

the value for that group is 11.5 percent. The small sample limits the value of conclusions which may be drawn from these coefficients. They are presented, however, to show the approximate range in variability of some refractory products.

2. EFFECT OF KILN SETTING, LOAD, AND WEIGHT OF BRICK ON TENSILE PROPERTIES [10]

(a) KILN SETTING

The manner of setting bricks in the kiln for the burning operation does not vary materially throughout the industry. The greatest difference enters in the load to which the bricks are subjected because

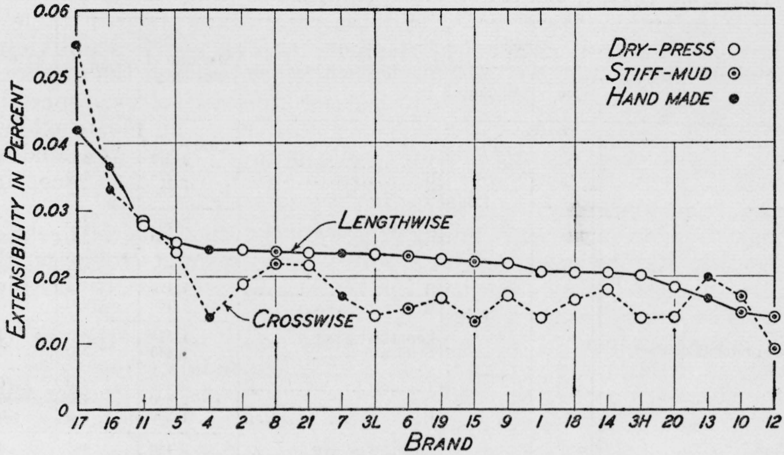

FIGURE 7.—*Graph showing the extensibility of specimens.*

The extensibility of specimens taken parallel to the 9 in. dimension of the br ck (lengthwise) is in most instances significantly greater than that of specimens taken parallel to the 4½ in. dimension (crosswise). The method of forming the brick is also indicated.

of the height of setting. Test results were obtained on one brand for the purpose of comparing the effect on tensile properties of bricks when: (1) set on end, (2) laid flat, and (3) set on edge. Data were obtained on bricks fired when set on end, flat, and on edge, in each case under 13 courses from the top of the setting, and also on bricks fired set on edge on the top course protected from direct heat by a layer of bricks laid flat. The load imposed on the top course of bricks was negligible and the bricks under 13 courses were under an approximate stress of 4.4 lb/in ^{2}. The results are given in table 5. Also included in the table for comparative purposes are data on bricks (brand 3L) fired set on edge but with no information on the height of the course in the kiln from which they were taken. These bricks were furnished at an earlier period by the same manufacturer who supplied the other bricks on which data are given in the table.

A comparison of the bricks burned on end, on edge, and flatwise under the weight of 13 courses shows that those burned on end have a much greater modulus of elasticity and strength lengthwise than crosswise. The average values of all lengthwise specimens for bricks

[10] In this phase of the study the conclusions drawn from the results are of limited value because only one product, one method of manufacture, and a small number of bricks were considered.

set on end give a Young's modulus 70 percent greater and a tensile strength 64 percent greater than the average values of all the crosswise specimens. If values for all specimens, both crosswise and lengthwise, from bricks under 13 courses are averaged according to method of setting, those set endwise showed greater elasticity and strength and lower extensibility than those set either edgewise or flatwise. The data indicate no particular difference in tensile properties between bricks burned edgewise and flatwise, with the exception that the crosswise specimens from bricks set flatwise have a lower modulus of elasticity and greater extensibility than the crosswise specimens from bricks set either edgewise or endwise.[11]

TABLE 5.—*Effect of kiln setting and weight of firebrick on tensile properties*

Method of setting	Brick No.	Brick Weight	Specimen [2] no.	Modulus of elasticity	Strength	Extensibility
		lb		1,000 lb/in.[2]	lb/in.[2]	%
End, under 13 courses	2	7.55	T	2,240	400	0.0180
			B	2,270	440	.0195
			E	1,280	275	.0215
			Lengthwise avg	2,255	420	.0185
			Brick avg	1,930	370	.0195
	4	7.59	T	1,735	380	.0220
			B	1,420	315	.0220
			E	1,160	240	.0205
			Lengthwise avg	1,575	345	.0220
			Brick avg	1,440	310	.0215
	3	7.65	T	2,480	480	.0195
			B	2,480	490	.0200
			E	1,260	250	.0200
			Lengthwise avg	2,480	485	.0195
			Brick avg	2,075	410	.0200
			Lengthwise avg	2,105	420	.0200
			Crosswise avg	1,235	255	.0205
			Setting avg	1,815	365	.0205
Edge, under 13 courses	5	7.54	T	1,430	335	.0235
			B	1,370	330	.0240
			E	1,190	250	.0210
			Lengthwise avg	1,400	330	.0235
			Brick avg	1,330	305	.0230
	3	7.55	T	1,590	360	.0225
			B	1,410	315	.0225
			E	1,600	295	.0185
			Lengthwise avg	1,500	335	.0225
			Brick avg	1,535	320	.0210
			Lengthwise avg	1,450	335	.0230
			Crosswise avg	1,395	270	.0195
			Setting avg	1,430	315	.0220
Edge (3L)[3] height of setting unknown.	1		T	1,730	395	.0230
			B	1,650	390	.0235
			E	2,550	350	.0140
	2		T	1,820	425	.0235
			B	1,590	365	.0230
			E	2,690	340	.0125
	3		T	1,100	270	.0245
			B	1,280	285	.0225
			E	2,350	365	.0155

[1] Refers only to brand 3, made by the dry-press method of forming.
[2] Sampled in accordance with method illustrated in figure 1, also figure 6 (brick III).
[3] Refers to brand 3L.

[11] It may be concluded that bricks set flatwise during firing should prove superior in installations of header construction where thermal spalling is an important consideration.

TABLE 5.—*Effect of kiln setting and weight of firebrick on tensile properties*—Con.

Method of setting	Brick No.	Brick Weight	Specimen no.	Modulus of elasticity	Strength	Extensibility
		lb		1,000 lb/in.	lb/in.	%
Edge (3L) height of setting unknown.			Lengthwise avg	1, 530	355	.0235
			Crosswise avg	2, 530	350	.0140
			Setting avg	1, 860	355	.0200
Flat, under 13 courses	4	7. 29	T	1, 375	300	.0215
			B	1, 250	280	.0225
			E	855	210	.0245
			Lengthwise avg	1, 315	290	.0220
			Brick avg	1, 160	265	.0230
	5	7. 54	T	1, 100	245	.0220
			B	1, 040	265	.0255
			E	920	235	.0260
			Lengthwise avg	1, 070	255	.0240
			Brick avg	1, 020	250	.0245
	2	7. 58	T	1, 750	435	.0250
			B	1, 700	410	.0240
			E	1, 530	315	.0205
			Lengthwise avg	1, 725	420	.0245
			Brick avg	1, 660	385	.0230
			Lengthwise avg	1, 370	320	.0235
			Crosswise avg	1, 100	255	.0235
			Setting avg	1, 280	300	.0235
Edge, under 1 course	4	7. 52	T	1, 845	390	.0210
			B	1, 280	265	.0210
			E	1, 360	255	.0185
			Lenthwise avg	1, 560	320	.0210
			Brick avg	1, 495	305	.0200
	2	7. 56	T	2, 040	355	.0175
			B	1, 925	420	.0215
			E	1, 540	335	.0215
			Lengthwise avg	1, 980	385	.0195
			Brick avg	1, 835	370	.0200
	5	7. 66	T	2, 635	485	.0185
			B	2, 185	420	.0195
			E	2, 280	505	.0220
			Lengthwise avg	2, 415	450	.0190
			Brick avg	2, 370	470	.0200
			Lengthwise avg	1, 985	390	.0200
			Crosswise avg	1, 725	365	.0210
			Setting avg	1, 900	380	.0200

(b) LOAD

Whether specimens during firing were subjected to axial or lateral load depended on the method of setting in the kiln. In figure 8 bars representing tensile properties are designated H and V to indicate which specimens were in a horizontal position under lateral load, and those in a vertical position under axial load during heating, irrespective of the setting or position of the brick. Horizontal-shading lines within the bars refer to specimens taken crosswise and vertical-shading lines to specimens taken lengthwise of the brick. Table 5 gives the actual values for the tensile properties of these specimens. This table and figure 8 show that the tensile properties are significantly affected by axial load. It is probable that the properties were also affected somewhat by lateral load, although no data are available to evaluate this effect.

In studying the effects of load on the tensile properties of the specimens, the *differences* in properties between crosswise specimens

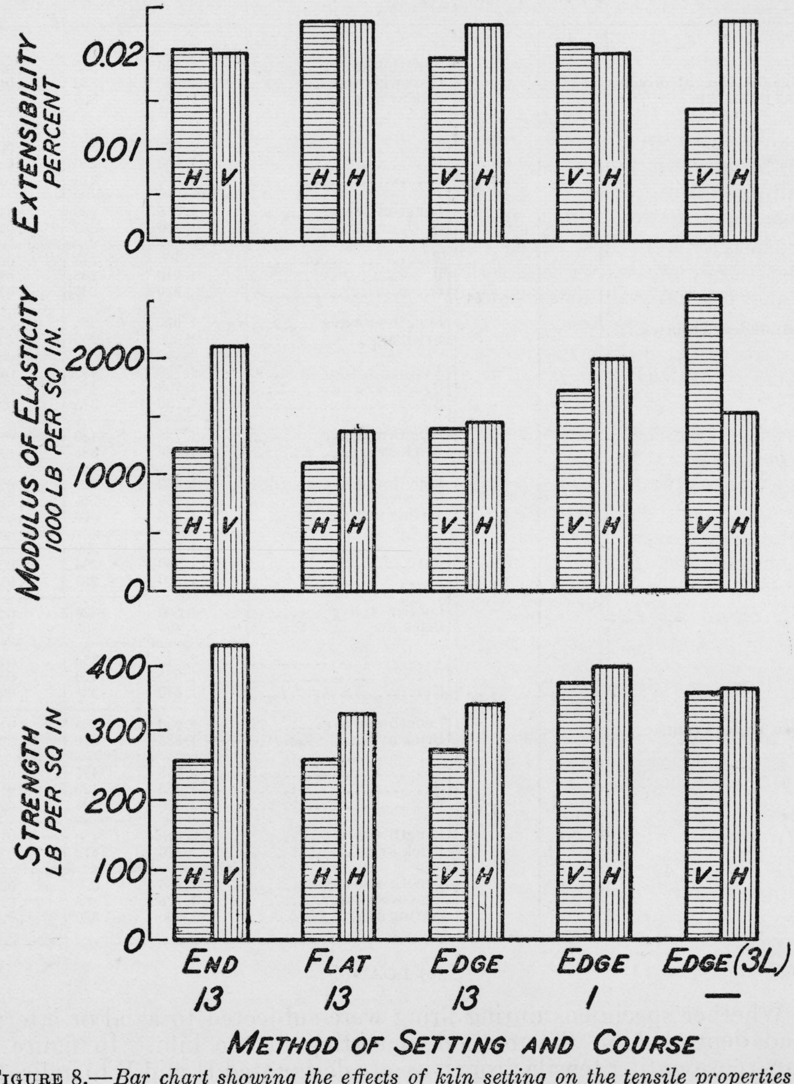

FIGURE 8.—*Bar chart showing the effects of kiln setting on the tensile properties of bricks.*

The bars made up of shading lines parallel to the base represent data on specimens taken crosswise to the brick whereas those made up of lines vertical to the base represent specimens taken lengthwise. The markings H and V indicate that axes of specimens during firing were horizontal or vertical, respectively.

and lengthwise specimens for any one method of setting were compared with these differences for other methods of setting. The difference in modulus of elasticity between vertical V and horizontal H specimens for the edge 1 setting is about the same as that between the crosswise and lengthwise specimens of the flat 13 setting (all specimens in horizontal H position) even though the mean modulus of elasticity of the edge 1 specimens is considerably greater than that of the flat 13 specimens. As far as axial loading of the specimens is concerned, both settings would be considered as under no load. However, when axial load is applied the modulus of elasticity of the vertical V specimens is increased relative to that of the horizontal specimens. This is especially apparent when the difference in modulus of elasticity between the H and V specimens from the bricks in the edge 1 setting is compared with that of the H and V specimens taken from bricks in the edge 13, end 13, and edge (3L) settings. The difference in height of the bars for the edge 1 specimens has been almost eliminated in the edge 13 specimens, and has actually been reversed in the end 13 and edge (3L) [12] specimens.

It may be noted further that the effect of axial load in the end 13 setting is similar to that in the edge (3L) setting, although in the first case the lengthwise specimens were under axial load, and in the second case the crosswise specimens were under axial load.

There is some tendency for the strength of the vertical, V, or axially loaded specimens to increase relative to that of the horizontal, H. The general effect of load on the extensibility is for that of the vertical specimens to be decreased relative to that of the horizontal specimens.

In analyzing these data the effect of heat treatment was not considered, but its effect may be observed by comparing, for example, the lengthwise average values of the properties (table 5) for bricks set edgewise under the weight of 13 courses with those for bricks set edgewise in the top course. It is probable that most of the difference in these average values was due to difference in heat treatment,[13] although it is probable also that the difference in lateral load had some effect.

(c) WEIGHT OF BRICK

Table 5 gives the weights of the 11 dry-pressed bricks included in the study of the effects of method of kiln setting on tensile properties. The weights ranged from 7.29 to 7.66 lb. The relation between weight and modulus of elasticity was determined for each method of setting. In 9 out of 11 cases the Young's modulus increased with weight.[14] However, because of the small number of samples, the value of a quantitative evaluation of the relation would be limited, and this relation might not apply to either the stiff-mud or the handmade process of manufacture.

VI. SUMMARY AND CONCLUSIONS

The tensile properties of 22 different brands of firebrick at room temperature were determined. The chemical composition, porosity, pyrometric-cone equivalent, and method of manufacture for most of the materials are included.

A testing machine of the simple lever type, especially constructed for the study, is described. Deformation measurements were

[12] The data lead to the conclusion, without any consideration for degree of temperature, that bricks edge (3L) were loaded under considerably more than 13 courses during kiln firing.

[13] R. A. Heindl and W. L. Pendergast, BS J. Research 3, 691 (1929) RP114.

[14] In forming dry-pressed bricks, the quantity of material filling the mold boxes varies, but the bulk volume of the resulting bricks is substantially the same and the difference in weight is, therefore, due to difference in quantity of material filling the mold box. The bulk volume of the bricks was not determined.

obtained with the Tuckerman optical strain gage, which permitted readings to be duplicated to within 0.000002 in.

Three different methods of obtaining specimens from the individual brick were tried, and the results of tests on selected specimens are given. In the method adopted, three specimens were machined from each brick, two lengthwise and one crosswise of the brick. The lengthwise specimens provided a 3-in. gage length and the crosswise a 2-in. gage length. All specimens had a cross-sectional area of 1.50 sq in. in the gage length.

The following results were obtained:

1. Based on strength and Young's modulus of elasticity of firebrick in tension, for the brick sampled both lengthwise and crosswise, the bricks may be generally classified into three types as follows: (*a*) These properties are approximately alike irrespective of the direction of sampling—handmade bricks were of this type; (*b*) these properties of lengthwise specimens are greater than those of the crosswise specimens—the stiff-mud bricks were of this type; and (*c*) the modulus of elasticity of the crosswise specimens is greater than that of the lengthwise specimens and the strengths are approximately equal—most of the dry-pressed bricks were of this type.

2. The range in extensibilities for all brands of bricks is from 0.0120 to 0.0465 percent, but the majority of firebricks are grouped within the comparatively narrow range from 0.0175 to 0.0235 percent. A highly siliceous fire-clay brick and a silica brick, with higher silica content than the other brands and both formed by the handmade process, had extensibilities much greater than the other brands.

3. In general, bricks formed by the dry-press process had greater extensibilities than those formed by either the handmade or the stiff-mud process.

4. When comparing the tensile properties of several bricks of the same brand, handmade bricks were more variable from one brick to the next than either stiff-mud or dry-pressed bricks. However, the range from maximum to minimum values for individual bricks is less for the handmade bricks than for either of the other types.

5. From the limited data obtained on bricks fired under no load, when compared with those fired under a load of 13 courses (stress approximately 4.4 $lb/in.^2$), it was noted that the tensile properties of the specimens subsequently cut from the bricks were significantly affected by axial load during heating. It is probable that the properties were also affected somewhat by lateral load, although no data were obtained to evaluate this effect. In those bricks fired under a load of 13 courses the difference in the modulus of elasticity and in the strength lengthwise and crosswise was greater in the bricks burned on end than in those set edgewise or flatwise. Of the three methods, the end setting had also the highest modulus of elasticity and strength and the lowest average extensibility.

In general, the modulus of elasticity of dry-pressed bricks increased with the weight of the brick.

WASHINGTON, March 9, 1936.