U. S. Department of Commerce National Bureau of Standards

RESEARCH PAPER RP747

Part of Journal of Research of the National Bureau of Standard Volume 13, December 1934

YOUNG'S MODULUS OF ELASTICITY AT SEVERAL TEMPERATURES FOR SOME REFRACTORIES OF VARYING SILICA CONTENT

By Raymond A. Heindl and William L. Pendergast

ABSTRACT

Determinations of Young's modulus of elasticity of 10 brands of fire-clay bricks (ranging in silica content from 48 to 52 percent), 2 brands of silica bricks, and an 80 percent alumina fire brick, were made at room temperature, 100, 200, 400, 500, 600, and 800° C. In a few cases determinations were made also at 300, 700, and 900° C. Six samples were tested through temperature regions of crystalline silica inversions at intervals of less than 100° C. The data show that the modulus of elasticity is affected greatly by the total silica content, modified by the form of the crystalline silica present and by the temperature. A general relation was found between modulus of elasticity, total silica, and linear thermal expansion.

CONTENTS

I. INTRODUCTION

It has been shown[1] that the 3 properties, modulus of elasticity, linear thermal expansion, and modulus of rupture when considered together give a fairly good measure of the resistance of heated clay

[1] F. H. Norton. J. Am. Ceramic Soc. 8,29(1925). M. C. Booze and S. M. Phelps. J. Am. Ceramic Soc. 8,361(1925). R. A. Heindl and W. L. Pendergast. BS J. Research 3,691(1929)RP114. K. Endell. Glastech. Ber. 11,178(1933). R. A. Heindl and L. E. Mong. J. Am. Ceramic Soc. 16,601(1933).

94127—34——7

ware to thermal shock. In a previous publication[2] it was reported that the modulus of elasticity of fire-clay brick was greater in most cases at 550° C than at 20° C and that the increase was not proportional to the value obtained at the lower temperature. Because of the large differences in percentage increase in Young's modulus of elasticity for the several brands of bricks tested at those 2 temperatures, it seemed logical to measure the modulus at several intervening temperatures in order to determine whether the changes were gradual or abrupt. At the same time some information might be gained as to the cause of such changes in the modulus of elasticity[3] which accompany increases in temperature.

II. MATERIALS

The fire-clay bricks used in this study were chosen from the 17 brands reported on in a previous publication,[4] but were received subsequent to the original shipment. The brands, 10 in number, were selected so that a series of bricks of a wide range in silica content would be included. In addition, 2 brands of silica bricks and an 80-percent alumina brick were investigated.

1. SILICA CONTENT

The bricks were analyzed for silica content by the sodium carbonate fusion method. It was the only chemical determination.[5] The fire-clay bricks ranged in silica from 47.8 to 81.9 percent. The silica bricks contained 96 percent silica and the high alumina brick 15.7 percent.

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.[6] The values, which are given in table 1, were included to indicate that, with one exception (brand J), the materials were of a grade of refractoriness that would preclude the formation of appreciable quantities of glass when reheated at 1,400° C for 5 hours. Eight of the 10 fire-clay brick have a pce of 31 or above.

---

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

[3] The results of similar studies of the elastic properties of ceramic bodies have been given in the following reports: R. Rieke and S. Muller, *The elasticity and plastic softening of some sagger clays and of porcelain.* Ber. Deut. Keram. Ges. **12**,419(1931). K. Endell and W. Mullensiefen, *On the elastic distortion and plastic deformation of refractory bricks at 20° and at higher temperatures.* Ber. Deut. Keram. Ges. **14**,16(1933). A. L. Roberts and J. W. Cobb, *Behavior of refractories under torsion at different temperatures.* Trans. Ceramic Soc. **32**(1933).

[4] See footnote 1, p. 851.

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

[6] American Society for Testing Materials Book of Standards for 1933, pt. 2, p. 184.

TABLE 1.—*Silica content and some properties of the refractories*

Brand [1]	Silica content [2]	pce [5]	Tested as received from manufacturer										Tested after reheating for 5 hours at 1,400° C								
			Porosity	Young's modulus of elasticity (1,000 lb/in.²) at—									Porosity	Young's modulus of elasticity (1,000 lb/in.²) at—							
				20° C	100° C	200° C	400° C	500° C			800° C	900° C		20° C	100° C	200° C	400° C	500° C	600° C	700° C	800° C
	Percent	*Cone no.*	*Percent*										*Percent*								
Q	47.8	33	15.2	1,990	1,960	2,120	2,220	2,210	2,270	2,100	1,075	770	14.5	2,920	2,890	2,910	2,880	2,990	3,040	3,150	1,510
C	51.1	33	20.5	680	710	890	1,050	1,220	1,270	-------	950	-------	20.0	1,830	1,895	2,045	2,240	2,260	2,360	-------	2,020
B	53.6	32	21.9	1,550	1,800	2,020	2,050	2,410	2,600	-------	2,360	1,140	20.4	3,860	4,290	4,620	5,080	5,250	5,570	4,715	4,170
R	55.5	32 to 33	23.0	3,410	3,000	3,600	3,920	4,260	4,760	4,720	4,050	-------	21.9	3,610	3,800	4,400	4,690	5,470	6,200	-------	4,960
E	55.2	32 to 33	16.5	1,570	1,560	1,640	1,940	2,060	2,210	2,190	2,070	1,280	15.6	3,580	3,820	4,200	4,500	4,630	4,660	-------	4,270
I	56.7	31	24.0	580	570	610	720	770	950	-------	940	-------	18.8	2,510	2,540	2,680	2,980	3,270	3,510	-------	2,230
J	60.3	28 to 29	13.1	2,560	2,590	2,740	2,930	3,120	3,620	-------	3,040	-------	9.6	5,820	5,850	5,960	6,300	6,740	6,050	-------	4,450
G	66.6	32 to 33	31.4	990	940	1,120	1,260	1,420	2,240	2,400	2,130	1,690	29.0	1,360	1,340	1,360	1,770	2,020	2,800	3,170	2,980
P	69.7	30 to 31	26.6	1,520	1,410	1,530	1,890	2,180	3,400	-------	3,080	-------	23.9	2,300	2,190	2,340	3,270	3,920	4,860	5,175	5,040
H	81.9	31	30.3	350	360	365	495	645	1,380	1,630	1,410	-------	30.4	390	340	355	570	680	1 390	1,660	1,520
X[3]	96.3	32	32.4	1,060	830	630	1,300	1,990	2,270	2,070	1,620	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Y[3]	96.0	32 to 33	28.9	450	400	330	590	770	1,040	1,320	970	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Z[4]	15.7	Over 37	38.8	2,700	2,700	2,770	2,800	3,030	3,335	3,100	2,270	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

[1] Key letters of fire-clay brick correspond to those referred to in BS Research Pap. RP114.
[2] The silica content of the 80 percent alumina brick was furnished by the manufacturer of the brick.
[3] Silica brick, modulus of elasticity values (lb/in.²) at:

	160° C	300° C	550° C	650° C
(X)	510,000	950,000	2,140,000	-------
(Y)	340,000	470,000	890,000	1,280,000

[4] High alumina brick.
[5] Pyrometric cone equivalent.

3. POROSITY

The procedure for making the porosity determinations was as follows. Three specimens, 1 by 1 by 2 inches, of each brick were saturated by boiling them in water for 2 hours and allowing them to cool in the water overnight. The porosity was taken as the ratio of the volume of water absorbed to the bulk volume of the specimen.

The porosities are given in table 1, both for the bricks as received from the manufacturer and after reheating in a laboratory furnace at 1,400° C for 5 hours. The values for the fire-clay bricks range from 13.1 to 31.4 percent for the samples as received and from 9.6 to 30.4 percent for the same samples after reheating. It is evident that in the majority of cases the reheating does not appreciably affect the porosity.

III. METHODS OF TESTING

1. LINEAR THERMAL EXPANSION

The data on linear thermal expansion (figs. 2 and 3) were taken, with 2 exceptions (brands G and H), from the report previously cited.[7] Specimens approximately ⅞ by ⅞ by 6 inches were used for the tests. which were made as described in that report.

2. YOUNG'S MODULUS OF ELASTICITY

The apparatus used and the method for determining Young's modulus of elasticity have been described in other publications.[8] However, a change was made from wire-resistance units to recrystallized silicon carbide units for heating the furnace. In making this change the interior dimensions of the furnace were not affected, but additional insulating material was placed in the walls. The apparatus and rebuilt furnace are shown in figure 1.

One brick of each brand was cut into specimens 1 by 1 by 9 inches, and 2 or more from each brick were tested in flexure as received from the manufacturer and also after having been reheated at 1,400° C for 5 hours in a laboratory furnace. Tests were made at the following temperatures: room (approximately 20° C), 100, 200, 400, 500, 600, and 800° C. A few specimens were also tested at 300, 700, and 900° C. The results are given in table 1. One specimen each of 6 brands was tested at intervals of less than 100° C through the temperature regions of crystalline silica inversions.

IV. RESULTS AND DISCUSSION

1. EFFECTS OF REHEATING AND OF VARIOUS TEMPERATURES ON YOUNG'S MODULUS OF ELASTICITY

In figures 2 and 3 each group of curves refers to an individual specimen. Comparison of the dotted and solid curves shows the changes which have taken place in the elasticity of the bricks due to the reheat treatment. The elasticities, expressed as moduli, determined at the various temperatures of test are plotted in the figures as open circles. Figure 2 shows the values for those bricks which after reheating have a maximum modulus of elasticity below 3,500,000 lb/in.^{2} and

[7] R. A. Heindl and W. L. Pendergast, BS J.Research 3,691(1929)RP114.
[8] R. A. Heindl and W. L. Pendergast, BS J.Research 3,691(1929)RP114. J. Am. Ceramic Soc. 10,524 (1927).

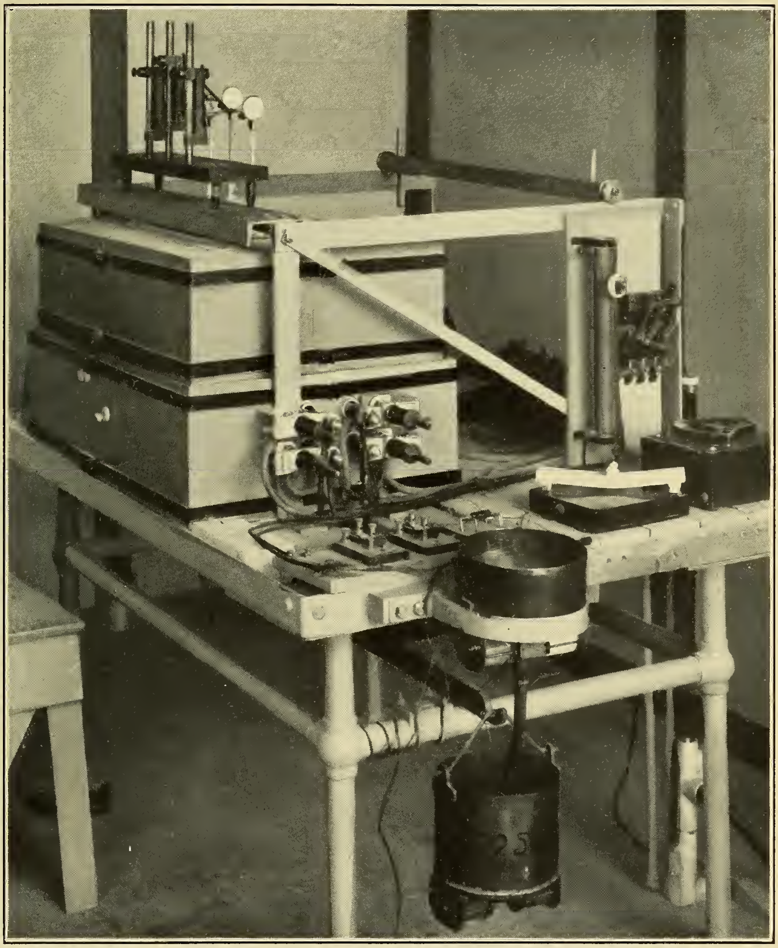

FIGURE 1.—*Furnace and equipment used in determining Young's modulus of elasticity of refractory brick by flexure tests.*

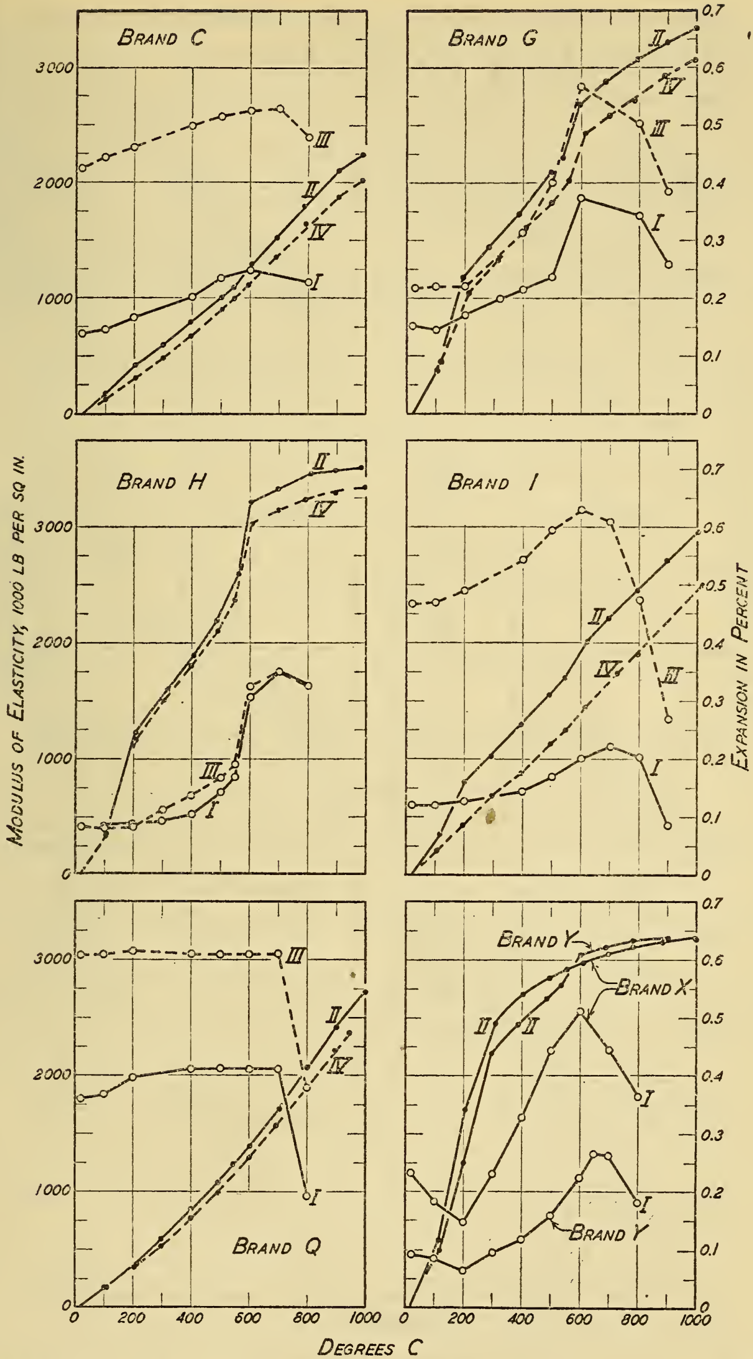

FIGURE 2.—*Young's modulus of elasticity (open circles), and linear thermal expansion (solid circles), of specimens cut from refractory brick.*

Values for a series of different temperatures are given as obtained on the material received from the manufacturer (identified by I and II) and also after reheating in laboratory furnaces at 1,400° C (identified by III and IV).

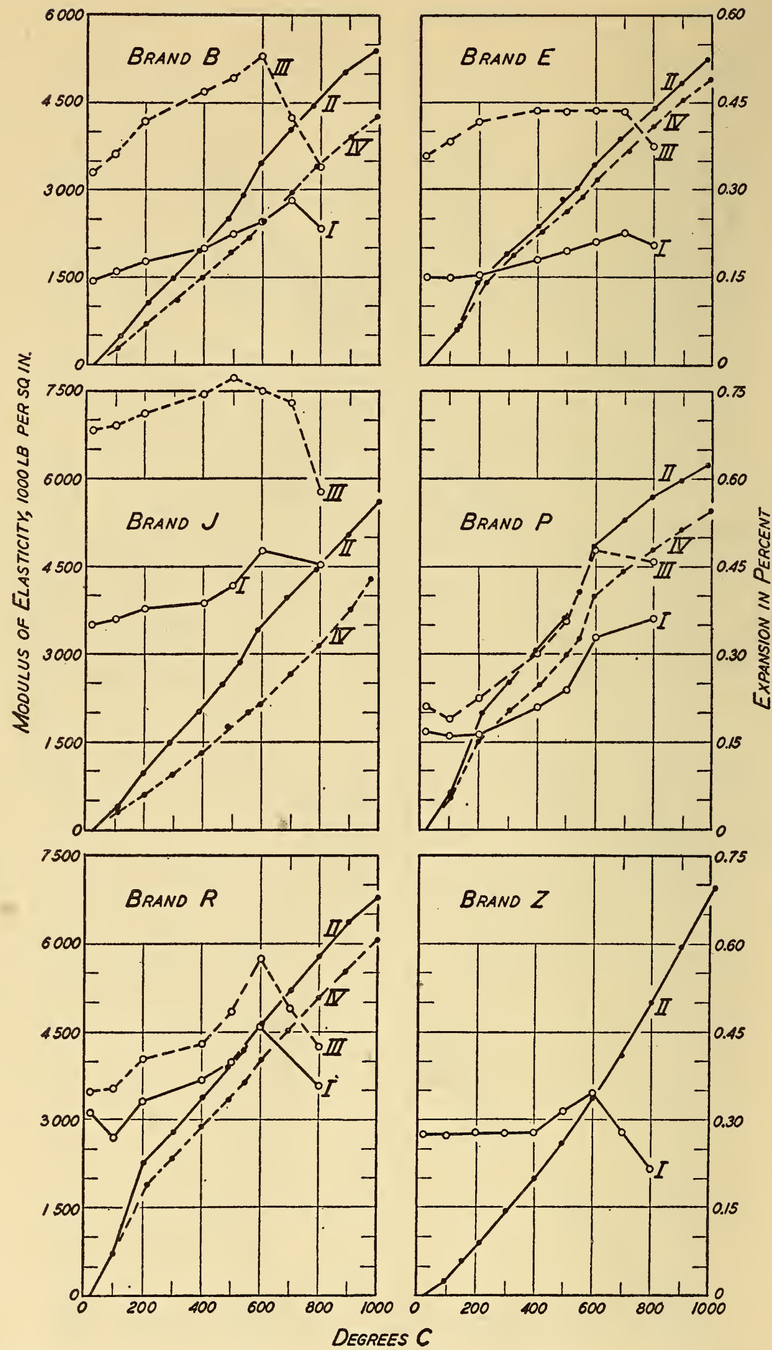

FIGURE 3.—*Young's modulus of elasticity (open circles), and linear thermal expansion (solid circles), of specimens cut from 5 brands of refractory brick and 2 brands of silica brick.*

Values are given as obtained at a series of different temperatures on material as received from the manufacturer (identified by I and II) and also after heating in laboratory furnaces at 1,400° C (identified by III and IV).

the values in figure 3 are for bricks having a maximum modulus above 3,500,000 lb/in.[2] The corresponding linear thermal expansions are plotted as solid circles (scale at the right) for each of the bricks to show conveniently whether or not crystalline silica is present in appreciable quantities.

Although the lines connecting the values of the modulus of elasticity, obtained at the various temperatures, are in general parallel for the reheated and nonreheated specimens (figures 2 and 3), it is evident that the reheating in most cases did increase greatly the values for any one temperature.[9]

It was found that the modulus of elasticity of each of the 2 brands of silica bricks and also that of brands H (reheated), P and R (non-

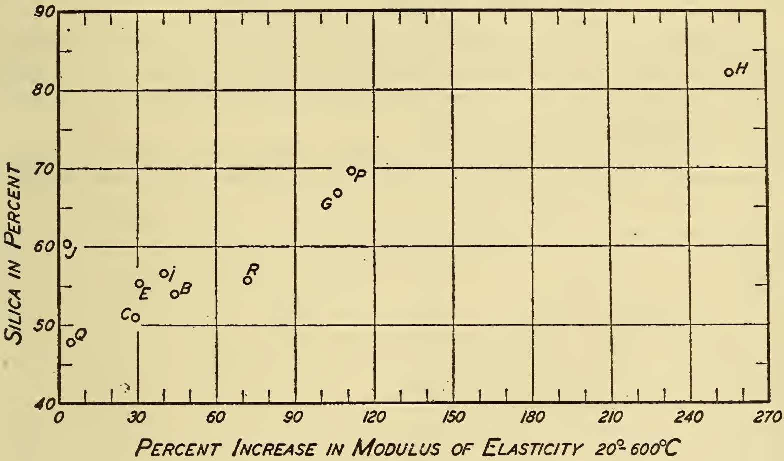

FIGURE 4.—*Relation between the percentage change in Young's modulus of elasticity for the temperature range 20 to 600°* C *and the silica content of fire-clay brick.*

reheated) was slightly lower at 100° C than at 20° C, and in every case the maximum modulus of the refractories was found at, or below, 700° C.

In general, the figures show that the modulus of elasticity for brand Q remained practically constant between 20 and 700° C; for brands G, H, J, P, and R the increase in the modulus was small but gradual between 20 and 500° C and rather large between 500 and 600° C; for brands B, C, E, and I the increase was gradual between 20 and 600° C. For the silica bricks the modulus decreased sharply between 20 and 200° C and increased fairly uniformly and rapidly between 200 and 600° C while, for the high alumina brick, the values remained constant to about 400° C and then increased uniformly to 600° C. It may be seen in most cases that the irregularities in the lines connecting the values of the modulus correspond to the temperature ranges in which inversions of crystalline silica take place.

[9] It was pointed out that the porosity of the bricks was not greatly affected by the reheat treatment. It follows that the porosity cannot be relied upon to give any information of such changes in elasticity. Furthermore, the porosity bears no apparent relation to the modulus of elasticity of bricks of approximately the same pce values.

2. RELATION OF MODULUS OF ELASTICITY TO SILICA CONTENT AND TO LINEAR THERMAL EXPANSION

(a) SILICA CONTENT

Figure 4 shows a relation between silica content and percentage change in modulus of elasticity from room temperature to 600° C as calculated from those values in table 1, which were obtained on the specimens reheated at 1,400° C. However, such a relation is apparently found only when bricks of approximately the same refractoriness are compared, since an exception to the relation is brought out in the case of brand J, which has a pce of only 28–29. A similar relation was noted for the samples tested as received.

(b) LINEAR THERMAL EXPANSION

A comparison of the expansion curves in figures 2 and 3 with the lines connecting the modulus of elasticity values shows that either a decrease or practically no change in modulus accompanied the inversion of tridymite and cristobalite.

The curves show further, with one exception (brand R), that wherever the rate of expansion increased between 500 and 600° C.,

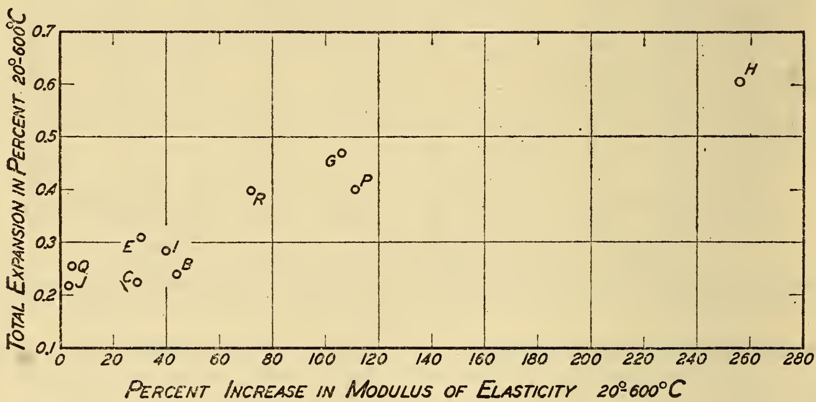

FIGURE 5.—*Relation between the total percentage change in Young's modulus of elasticity of fire-clay brick for the temperature range 20 to 600° C and the total percentage linear thermal expansion for the same range.*

caused by the inversion of alpha to beta quartz, there was also a large increase in modulus of elasticity. (For instance, in the case of specimen H the increase amounted to about 115 percent.) Petrographic examination of brick of brand R, which showed an appreciable increase in modulus of elasticity between 500 and 600° C, indicated a noticeable quantity of quartz even though the expansion curve failed to show its presence.[10]

The total linear thermal expansions, from room temperature to 600° C of the fire-clay bricks after having been reheated are plotted in figure 5 against the percentage change in modulus of elasticity for the same range in temperature. Changes in modulus of elasticity were based on the values given in table 1 and the expansions were taken from the curves in figures 2 and 3. It will be noted that a fairly consistent and approximately linear relation exists between the percentage change in elasticity and expansion of fire-clay brick.

[10] A similar phenomenon has been observed by J. B. Austin and R. H. H. Pierce, Jr. J. Am. Ceramic Soc. **16**,104(1933); and by R. G. Geller, D. N. Evans, and A. S. Creamer, BS J.Research **11**,327(1933)RP594.

3. EFFECT OF MODIFICATIONS OF UNCOMBINED SILICA ON MODULUS OF ELASTICITY

The trend of certain curves established by modulus determinations at 100° intervals indicated that significant changes in modulus might be established by making tests at smaller intervals, more particularly

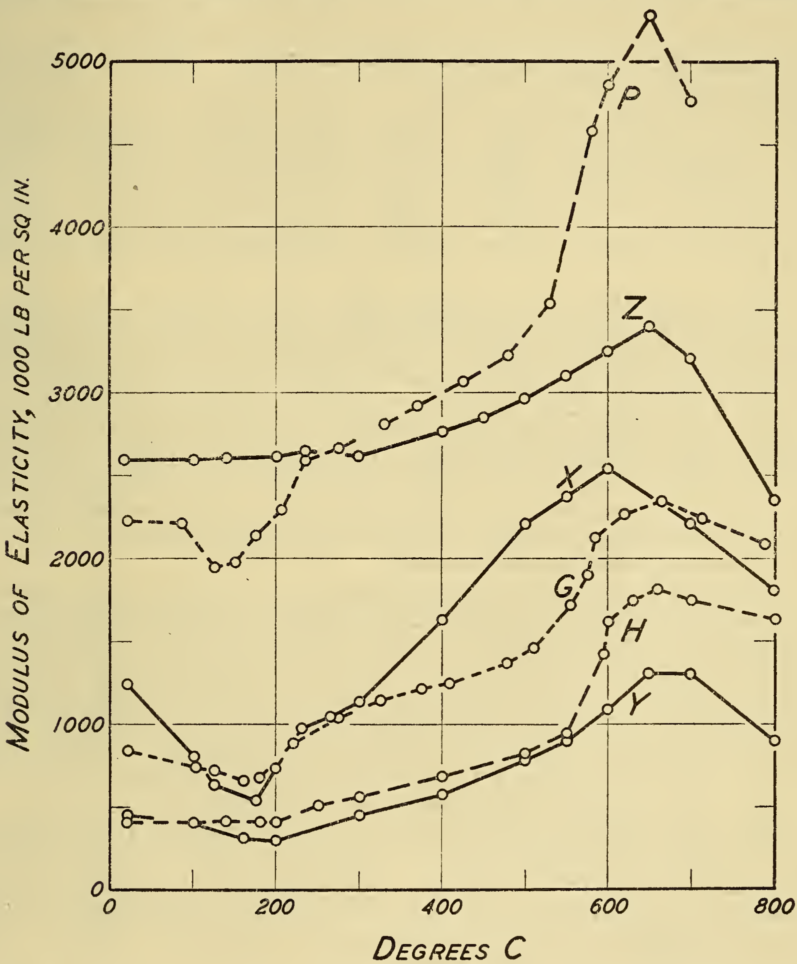

FIGURE 6.—*Young's modulus of elasticity of specimens cut from 6 brands of refractory brick.*

Values are given for intervals of less than 100° C through critical temperature ranges. Data on silica bricks X and Y and high alumina brick Z were obtained on the specimens as received from the manufacturer, and data on fire-clay bricks G, H, and P after the specimens had been reheated at 1,400° C for 5 hours.

with regard to changes in modulus which might accompany the large volume changes caused by the inversions of crystalline silica. Some measurements were, therefore, made at intervals of less than 100° C on 1 specimen each of fire-clay bricks of brands G, H, and P, 2 brands of silica bricks and the high alumina brick. The results [11] are shown

[11] Because it was necessary to use different specimens in these tests from those used for obtaining the results plotted in figures 2 and 3, the results do not necessarily check. This is illustrated by the values for the 3 specimens of a brick of brand H, table 2.

in figure 6. The modulus of elasticity for fire-clay bricks P and G and silica bricks X and Y was appreciably lower within the tridymite inversion temperature range (150 to 175° C) than at room temperature. The modulus for specimens of G, P, and X shows a marked increase between 175 and 230° C, which is within the temperature range of the cristobalite inversion; and those for specimens G, H, and P show a marked increase between 500 and 600° C, which covers the range of the alpha to beta quartz inversion. Each of the specimens shows a uniform increase in modulus between about 250 and 550° C, and the maximum modulus was reached at approximately 650° C. Although the high alumina brick Z and the highly siliceous brick H approximate extremes in composition, the modulus in both cases show little difference in trend between 20 and 550° C. At the latter temperature the modulus for Z continued to increase uniformly to 650° C, whereas the modulus for H increased markedly to about 600° C.

No quantitative petrographic tests were made of the relative quantities of quartz and cristobalite, but an estimate indicated specimen G contained about 3 times as much quartz as cristobalite; H contained less than half quartz, approximately one-third cristobalite and apparently no tridymite; P contained somewhat more quartz than cristobalite and tridymite combined; and R contained only a small percentage of quartz in comparison to the cristobalite. Silica brick X contained very little quartz and glass, and large amounts of cristobalite and tridymite with the latter in preponderance. Silica brick Y contained possibly as much as 25 percent quartz and noticeably less tridymite than specimen X.

Although in the case of the specimens G, P, X, and Y the modulus decreased noticeably between approximately 100 and 200° C, in no case was the value at 600° C lower than the value at 550° C. It would appear that the decrease in the modulus between approximately 100 and 200° C in these specimens is caused by the presence of considerable quantities of tridymite since very little decrease was observed in brick H, which apparently contained no tridymite. On the other hand, the great increase in modulus between 550 and 600° C is apparently caused by the presence of crystalline quartz.

The silica content of the 2 silica bricks is identical, yet differences in structure and mineralogical composition result in the 2 brands having quite different moduli at corresponding temperatures. As previously stated, silica brick X, which showed a much larger decrease in the modulus of elasticity between 100 and 200° C than Y, contained noticeably more tridymite.

4. EFFECT OF SLOW COOLING AND QUENCHING ON MODULUS OF ELASTICITY

When attempting to obtain check results by making duplicate measurements on a specimen that had been tested through the range of temperatures outlined it was noted that the values were lower than those obtained in the first test. It was believed that the slow cooling or perhaps partial annealing treatment of the specimens was responsible for the change. Table 2 gives the results obtained on a few samples of bricks before and after slow cooling from 800° C. In addition, some of the specimens were quenched in air from 800 and 1,000° C to determine whether or not strains would be set up by the

TABLE 2.—*Modulus of elasticity of refractory brick at room temperature. Showing effect of slow cooling versus quenching*

Brand	Young's modulus of elasticity (1,000 lb/in.²)				
	Original test	Tested after—			
		Slow cooling from 800° C	Quenching in air from 800° C	First quenching in air from 1,000° C	Second quenching in air from 1,000° C
P	2,220	1,810	1,460	1,220	1,160
X	1,155	750	780	990	1,030
Y	450	240		300	
Z	2,790	2,550		2,720	
Ha	560	350			
Hb	400	270		210	170
Hc	290	220		160	80

rapid cooling treatment. It is interesting to note that the modulus of elasticity of the silica bricks X and Y increased with the quenching treatment and that the modulus of elasticity of the siliceous brick (P and H) continued to decrease. Within limits, such a decrease is believed to be beneficial with respect to increased resistance to thermal shock. Although the modulus of the high alumina brick Z also increased with the quenching treatment, the change was not appreciable.

V. SUMMARY AND CONCLUSIONS

Ten brands of fire-clay bricks covering a wide range in silica content (48 to 82 percent silica); 2 brands of silica bricks (96 percent silica); and 1 of high alumina bricks (16 percent silica), were selected and Young's modulus of elasticity determined for each. The fire-clay bricks were tested as received from the manufacturer and also after reheating in a laboratory furnace at 1,400° C for 5 hours. The effect on the modulus of elasticity of the pce and porosity and the form or forms of uncombined silica was also studied.

After testing the bricks at 20, 100, 200, 400, 500, and 600° C, it was found that, with one exception, the modulus of elasticity was affected significantly by the temperature. For 5 brands of fire-clay bricks the modulus increased gradually between 20 and 500° C and rather abruptly between 500 and 600° C; for 4 other brands of fire-clay bricks the increase was gradual between 20 and 600° C; for the 2 brands of silica bricks the modulus decreased from 20 to 175° C and increased from 175 to 600° C. The decrease of the modulus in the lower temperature range was noted also in highly siliceous fire-clay bricks. The modulus of the high alumina brick remained constant to 400° C, then increased gradually to 600° C.

There is a fairly consistent and approximately linear relation between percentage increase in modulus of elasticity between room temperature and 600° C and the silica content, and also the total linear thermal expansion, provided the bricks are of approximately the same refractoriness and have not been heated sufficiently high to dissolve the silica.

On testing 2 silica bricks and 3 highly siliceous fire-clay bricks at temperature intervals of less than 100° C, it was found (except for 1 fire-clay brick) that the modulus of elasticity decreased at the approximate temperature of inversion of tridymite, increased at the approximate temperature of inversion of cristobalite and that, in every case, the inversion of quartz caused an increase.

Several specimens were tested before and after having been cooled comparatively slowly from 800° C. Results indicated that the modulus of elasticity was lowered by this treatment. On the other hand when the specimens were air-quenched from 800 and 1,000° C, the modulus of elasticity was decreased for the fire-clay bricks, increased for the silica, and the change in high alumina brick was practically negligible.

WASHINGTON, October 3, 1934.