PREPARATION OF EXPERIMENTAL SAGGER BODIES ACCORDING TO FUNDAMENTAL PROPERTIES

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ABSTRACT

This report presents the results obtained in a preliminary study of sagger bodies and contains data on the modulus of elasticity, transverse breaking strength, plastic flow, thermal expansion, and resistance to failure due to heat shock of 55 sagger mixes representing 39 different bodies fired at either 1,230° or 1,270° C. The 16 bodies prepared in duplicate were tested both after firing at 1,230° and 1,270° C. The bodies were prepared from a total of 15 different clays of known properties, and each body was made from two clays and a mixture of graded grog. The grog was graded into sizes so as to result in two types of bodies, those having (1) a coarse and open-grained structure and (2) a dense and fine-grained structure. The data on the fired bodies show that those containing the fine sizes of grog have the higher modulus of elasticity, transverse strength, and in the majority of cases, thermal expansion. Very little difference in total porosity of the two types of bodies is indicated although the rate of absorption shows great differences. The data obtained in this preliminary study indicate that those bodies having a porosity of less than 25 per cent, a low modulus of elasticity, as high transverse strength as is compatible with the low modulus of elasticity, and low thermal expansion below 250° C. are the most desirable for sagger purposes.

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I. INTRODUCTION

The investigation of the properties of sagger clays and sagger bodies is a study which readily resolves itself into a number of phases, each of which is more or less complete in itself. Results obtained in the study at the Bureau of Standards of several of these individual phases have been previously reported.¹ The present paper describes recent studies which included the preparation of sagger bodies based on fundamental data, the making of small experimental saggars, and the determination of certain physical properties of the fired saggars and sagger bodies. It contains the results of tests made on 39 different sagger bodies prepared in the laboratory and on eight sagger bodies furnished by pottery manufacturers as well as on saggars made from all these bodies.

II. GENERAL

A study of the sagger body compositions used by 40 pottery and tile manufacturers shows a large variation in the number and percentages of different clays used and percentage and sizing of grog. It also shows that the "rule-of-thumb" practice is largely followed in the compounding of sagger bodies. The number of clays used in any one body varies from two to four, and the amount of grog in the various bodies ranges from approximately 30 to 60 per cent. The majority of sagger mixes fail to show any definite sizing or grading of grog. In some cases the grog is simply crushed to pass a sieve with fairly large openings, while in others only the coarse grog is used. In general, the raw clay content of most sagger mixtures consists of one or more dense firing or vitrifying clays and one or more open-burning and comparatively refractory clays, with varying percentages and sizes of grog.

The possible variations in clay combinations, sizing, percentage, and porosity of grogs and firing temperatures is practically unlimited with the many sagger clays on the market. It was, therefore, necessary to limit this study to the making and testing of such body compositions from the 17 representative clays as might result in data of most value for preparing saggars of maximum life.

¹ I. Progress Report on Investigation of Sagger Clays, *J. Am. Ceram. Soc.*, **9** (3), pp. 131-143; 1926. II. Progress Report on Investigation of Sagger Clays—Some Observations as to the Significance of Their Thermal Expansion, *J. Am. Ceram. Soc.*, **9** (9), pp. 554-574; 1926. III. Progress Report on Investigation of Sagger Clays—Their Elasticity and Transverse Strength at Several Temperatures, *J. Am. Ceram. Soc.*, **10** (7), pp. 524-534; 1927. IV. Progress Report on Investigation of Sagger Clays—Their Elasticity, Transverse Strength, and Plastic Flow at 1,000° C., *J. Am. Ceram. Soc.*, **10** (12), pp. 995-1004; 1927.

III. SAGGER BODY COMPOSITIONS

The initial study of the compounding of sagger bodies included the blending of two clays, in equal parts by weights, mixed with equal proportions by weight of grog prepared from each clay. One of the clays when fired had a high porosity (open-burning) and the other a somewhat lower porosity (close-burning). The grogs used in these mixes were fired at approximately 1,230° C. (cone 9-9½) for one and one-half hours. This procedure was varied in several instances by using separately grog prepared from only one of the clays; that is, either the open-burning or the dense-burning clay. With one exception, only clays having the same general type of thermal expansion below 200° C. were used in a body; that is, each of the clays making up a body was taken from either group H or group L.² The sagger body numbers, the clays and grogs making up the various bodies, and the properties of these clays fired at 1,230° C. are given in Table 1.

The majority of the bodies were prepared in two series as similar as possible in every respect with the exception of the sizes of the grog. One series compounded with comparatively coarse sizes of graded grog was designated as "C" and the other series compounded with the finer sizes of graded grog was designated as "F." Two combinations of grog sizes were taken from those recommended by Kirkpatrick.³ The one, consisting of the relatively coarser sizes of grog, is recommended where resistance to repeated heating and cooling is desired more than strength. In the other, finer sizes are used and resistance to repeated thermal shock is sacrificed to obtain bodies of greater strength.

In the two primary combinations used, the grog sizing and the percentage of each size are as follows:

Material	Sieve No.		Percentage of each size
	Passed—	Retained on—	
For coarse grogged body-----	4	8	20
	8	12	60
	12	20	20
For fine grogged body-----	20	40	66⅔
	40	80	33⅓

² Report II (footnote 1) states that the clays have been classed in two groups according to thermal expansion behavior between 100° and 200° C.; clays classed in Group L showed a decided increase in the rate of expansion, while clays of Group H showed a very small, or, in the majority of cases, no increase in rate of expansion.

³ B. S. Tech. Paper No. 104, p. 33, Table 11.

TABLE 1.—Data on clays¹ fired at 1,230° C. used in sagger bodies

Sagger body Nos.	Num- bers of clays in sagger bodies	Grog No.	Belong to group ² —	Po- rosity	Tested at 20° C. Modulus of—		Saggers made from single clays cracked at—
					Rup- ture	Elas- ticity	
				Per cent	Lbs./in. ²	1,000 lbs./in. ²	° C.
1F, 1C, 1aF, 1aC.....	{ 24 37	24 37	H H	29 3	2, 180 3, 920	2, 770 9, 430	570 480
2F, 2C, 2aF, 2aC.....	{ 24 32	24 32	H H	29 13	2, 180 2, 310	2, 770 5, 610	570 515
3F, 3C, 3aF, 3aC.....	{ 19 32	19 32	H H	34 13	1, 380 2, 310	1, 530 5, 610	800 515
4F, 4C, 4aF, 4aC, 21SF, 4XF, 4XC.....	{ 19 24	19 24	H H	34 29	1, 380 2, 180	1, 530 2, 770	800 570
5F, 5C, 5aF, 5aC, 1XF, 1XC.....	{ 5 41	5 41	L L	22 36	3, 140 2, 350	4, 910 3, 110	370 350
6F, 6C, 6aF, 6aC, 20SF, 2XF, 2XC.....	{ 6 25	6 25	L L	32 34	600 2, 450	889 3, 570	410 495
7F, 7C, 7aF, 7aC, 3XF, 3XC.....	{ 15 42	15 42	H H	15 24	3, 305 1, 460	5, 210 2, 230	580 745
15S, 8F, 8C, 8aF, 8aC.....	{ 5 16	5 16	L L	22 42	3, 140 635	4, 910 934	370 1, 000
9F, 9C.....	{ 15 42	15	H H	15 24	3, 305 1, 460	5, 210 2, 230	580 745
10F, 10C.....	{ 6 5	6	L L	32 22	600 3, 140	889 4, 910	410 370
11F, 11C.....	{ 41 35	41 35	L H	36 14	2, 350 3, 360	3, 110 3, 360	350 575
12F, 12C.....	{ 24 39	39	H H	29 19	2, 180 3, 370	2, 770 5, 090	570 565
13F, 13C.....	{ 18 49	49	L L	17 37	3, 010 1, 710	5, 950 2, 370	405 460
14F, 14C.....	{ 18 49	18 49	L L	17 37	3, 010 1, 710	5, 950 2, 370	405 460

¹ Complete chemical and physical properties of these clays have been given in the four progress reports already published on this investigation. (See footnote 1 of text.)

² The second progress report (see footnote 1 of text) classed the clays according to rate of thermal expansion below 200° C. into Groups H and L.

The following special combinations of grog were used in one body each ("S" bodies):

1. Body 15S. Grog and dust passing an 80-mesh sieve.
2. Body 21S. F. Grog graded as follows to obtain a dense and strong body:

Sieve No.		Percent- age used
Passed—	Retained on—	
20	40	40
40	80	20
80	200	40

3. Body 20S. F. Grog approximately graded in accordance with W. F. Fuller's curve⁴ to obtain a body especially resistant to thermal shock and also of good strength.

Sieve No.		Percent- age of each size
Passed—	Retained on—	
4	8	20
8	12	15
12	20	20
20	40	15
40	80	15
80	200	15

In addition, eight bodies were prepared, four each using the coarse and fine grog combinations, except that the grog was fired for one and one-half hours at $770^{\circ} \pm 5^{\circ} \text{C.}$, instead of $1,230^{\circ} \text{C.}$ These bodies ("X" bodies) were so prepared because it has been found that fire clays show a rapid contraction at about 800°C. ⁵ It was assumed that it might be desirable to use grog which has not been fired higher than this temperature so as to eliminate the strains which are likely to be set up between the bond and grog during firing if the latter had been first fired at a temperature considerably higher than 800°C.

IV. DESCRIPTION OF SPECIMENS

The grog used in the preparation of specimen bars and saggars had been fired in all cases to approximately $1,230^{\circ} \text{C.}$ (cone $9\frac{1}{2}$). Six bars 1 by 1 by 12 inches were prepared for the determination of modulus of elasticity and transverse strength. Specimens measuring approximately 1 by 1 by 6 inches were used for linear thermal expansion studies. These specimens were cut to size from the ruptured 1 by 1 by 12 inch bars used for modulus of elasticity determinations. Six specimens 1 by 1 by 7 inches were made for dry breaking-strength tests and five (in some cases six) saggars, 4 by 4 by 6 by $\frac{1}{2}$ inches, were made for the thermal-shock test. The saggars were made oval in shape to more nearly simulate the conditions producing strains developed in saggars used in practice. One set of saggars and the 12-inch bars were fired at approximately $1,230^{\circ} \text{C.}$ (cones $9-9\frac{1}{2}$) and another set of each at $1,270^{\circ} \text{C.}$ (cones $11\frac{1}{2}-12$). To simulate industrial conditions which might cause some difference in the properties of the burned bodies, the saggars of any one set were not all made on the same day but on different days. All saggars were fired in the same kiln, a part of each set of five saggars being fired at different times.

⁴ Concrete Plain and Reinforced, 1916 ed., by Taylor and Thompson.

⁵ The Behavior of Fire Clays, Bauxites, etc., on Heating, Trans. Eng. Cer. Soc., 22, p. 111; 1922-23.

V. METHODS OF TESTING AND RESULTS

The methods of determining the modulus of rupture, porosity, linear thermal expansion, resistance to thermal shock, modulus of elasticity, and transverse strength at room and elevated temperatures, and the plastic flow at 1,000° C., have been described in detail in the several previous reports.⁶ It might be well, however, again to give briefly the method used in the quenching test. Five specimen saggars of each of the bodies were heated at progressively higher temperatures and air quenched until fracture occurred. The initial quenching was from 350° C., the second 400° C., and for each succeeding quenching the temperature was increased 25° C. until the test sagger failed.

1. MODULUS OF RUPTURE, UNFIRED BODIES

The moduli of rupture of the various sagger bodies, both those prepared in the laboratory and those received from the potteries, are given in Tables 2 and 3.

The average modulus of rupture for the bodies containing the fine grog was found to be 160 lbs./in.², for the bodies containing the coarse grog 95 lbs./in.², and for the commercial bodies 75 lbs./in.².

⁶ See footnote 1, p. 420.

TABLE 2.—Properties of sagger bodies fired at 1,230° C.

Body No.	Numbers of clays in body ¹	Modulus of rupture of unfired body	Tested at 20° C.				Tested at temperature at which sagger failed in quenching test				Tested at 750° C.			Porosity	Coeffi- cient of expan- sion 20° to 250° C. $\times 10^{-6}$	Coeffi- cient of expan- sion 20° to 600° C. $\times 10^{-6}$	Total expan- sion in per cent of unit length $\frac{20^\circ \text{ to } 1,000^\circ \text{ C.}}{0.52}$	Resist- ance factor "R"
			Modulus of—		Com- puted outer fiber strain	Sagger failing at— °C.	Modulus of—		Com- puted outer fiber strain	Rup- ture	Elas- ticity							
			Lbs./in. ²	$\frac{1,000}{\text{lbs./in.}^2}$			Lbs./in. ²	$\frac{1,000}{\text{lbs./in.}^2}$										
	24, 37	90	2, 110	4, 805	0.04	640	2, 000	3, 515	0.04	17.3	1, 730	3, 970	0.03	5.2	5.9	0.52	4.3	
	24, 37	50	955	1, 775	0.05	835	885	1, 465	0.06	17.6	1, 090	2, 270	0.05	4.7	5.6	0.51	5.5	
	24, 32	195	1, 905	3, 605	0.05	560	2, 205	4, 630	0.05	19.9	2, 260	4, 730	0.05	6.7	6.4	0.55	4.3	
	24, 32	75	960	1, 525	0.06	680	985	2, 605	0.04	23.8	880	2, 890	0.03	6.6	6.4	0.54	4.2	
	19, 32	105	1, 345	3, 990	0.07	760	1, 940	3, 500	0.06	24.6	1, 780	4, 150	0.04	5.5	6.2	0.51	4.7	
	19, 32	70	745	1, 405	0.05	860	850	1, 530	0.06	24.3	1, 140	2, 640	0.04	5.5	6.0	0.50	4.0	
	19, 24	75	1, 095	1, 595	0.07	640	1, 610	2, 690	0.06	33.4	1, 700	2, 830	0.06	7.2	7.2	0.56	2.9	
	19, 24	70	620	890	0.07	645	910	1, 580	0.06	34.2	1, 090	1, 875	0.06	7.6	7.6	0.58	2.8	
	5, 41	205	1, 505	2, 490	0.06	445	1, 970	3, 520	0.06	28.4	1, 820	3, 880	0.05	8.9	7.3	0.60	3.0	
	5, 41	110	1, 045	1, 545	0.04	585	1, 805	2, 200	0.04	28.4	1, 820	3, 880	0.05	8.5	7.0	0.58	2.1	
	6, 25	185	1, 700	1, 700	0.07	550	1, 620	2, 850	0.06	31.6	2, 105	3, 370	0.06	10.0	8.3	0.62	2.7	
	6, 25	130	1, 560	1, 075	0.05	610	1, 920	1, 960	0.05	30.0	1, 920	2, 810	0.03	9.3	8.0	0.59	2.2	
	15, 42	185	1, 875	3, 755	0.05	610	1, 910	3, 330	0.04	19.2	2, 300	6, 060	0.04	4.5	5.4	0.49	4.8	
	15, 42	160	1, 330	3, 330	0.04	690	1, 315	3, 330	0.04	16.6	1, 200	4, 355	0.03	4.3	5.4	0.49	4.5	
	5, 16	135	1, 315	2, 220	0.06	450	1, 570	2, 650	0.06	35.5	1, 660	2, 670	0.06	8.9	6.9	0.58	2.9	
	5, 16	75	510	1, 000	0.05	500	720	1, 270	0.06	34.9	755	1, 210	0.06	7.8	6.5	0.55	2.5	
	15, 42	165	2, 025	4, 700	0.04	565	2, 020	5, 280	0.04	17.3	2, 320	6, 020	0.04	4.7	5.7	0.50	4.5	
	15, 42	105	1, 175	3, 160	0.04	630	1, 340	4, 285	0.03	18.2	1, 275	4, 000	0.03	4.3	5.4	0.50	4.5	
	6, 5	180	1, 460	2, 090	0.07	440	1, 890	2, 530	0.07	30.4	2, 600	4, 110	0.06	10.0	8.6	0.60	2.7	
	6, 5	85	425	540	0.06	560	750	1, 350	0.06	33.0	1, 100	1, 815	0.06	9.1	8.1	0.63	2.6	
	41, 35	250	1, 525	2, 495	0.06	565	1, 675	3, 505	0.05	24.5	2, 200	4, 000	0.05	7.0	6.2	0.53	4.0	
	41, 35	110	660	1, 340	0.04	715	770	2, 280	0.03	24.0	930	2, 460	0.04	6.6	6.1	0.52	3.5	
	24, 39	120	1, 980	3, 680	0.05	535	1, 865	3, 030	0.06	25.7	2, 180	4, 110	0.05	6.1	6.2	0.53	3.5	
	24, 39	80	940	2, 280	0.04	615	1, 200	3, 140	0.04	24.2	1, 030	3, 340	0.03	5.9	5.9	0.51	2.6	
	18, 49	130	1, 510	2, 020	0.07	585	1, 550	2, 805	0.06	35.1	1, 370	3, 220	0.04	6.7	6.0	0.51	3.6	
	18, 49	95	690	1, 390	0.05	725	1, 155	2, 555	0.05	31.9	1, 050	1, 825	0.06	6.4	6.0	0.51	2.7	
	14, 14	125	1, 510	2, 625	0.06	535	1, 490	3, 320	0.05	28.1	1, 900	3, 530	0.05	6.9	6.4	0.54	3.3	
	18, 49	85	770	1, 400	0.06	610	1, 130	2, 425	0.05	26.7	1, 950	2, 520	0.04	6.8	6.1	0.53	3.4	
	15, 5	158	2, 935	3, 625	0.07	350	2, 790	4, 300	0.06	28.8	2, 460	4, 670	0.05	9.8	7.5	0.58	3.0	
	5, 41	170	3, 250	5, 335	0.06	465	5, 750	7, 010	0.05	19.4	3, 670	7, 010	0.05	19.4	---	---	---	
	5, 41	65	1, 350	2, 380	0.06	585	1, 245	2, 960	0.04	20.9	1, 400	3, 410	0.04	14.0	---	---	---	
	6, 25	180	2, 240	3, 255	0.07	445	1, 510	3, 620	0.07	29.6	2, 540	3, 980	0.06	29.6	---	---	---	
	6, 25	75	910	1, 645	0.06	590	1, 530	2, 960	0.05	29.0	1, 360	3, 980	0.03	29.0	---	---	---	
	15, 42	260	3, 985	7, 185	0.06	465	3, 090	7, 510	0.05	7.6	3, 700	9, 165	0.04	7.6	---	---	---	
	15, 42	145	1, 825	3, 340	0.05	590	1, 855	5, 890	0.03	12.0	1, 800	6, 025	0.03	12.0	---	---	---	
	19, 24	95	1, 585	2, 110	0.07	625	1, 890	4, 070	0.05	31.4	2, 400	4, 400	0.05	5.5	6.7	0.53	3.5	
	19, 24	80	1, 215	1, 740	0.07	665	1, 490	2, 900	0.05	30.4	1, 780	3, 300	0.05	4.8	6.5	0.50	3.4	

¹ Identification numbers of clays correspond to those used in previous reports published on this investigation.

TABLE 3.—*Properties of sagger bodies fired at 1,270° C.*

Body No.	Num- bers of clays in body ¹	Tested at 20° C.			Tested at temperature at which sagger failed in quenching test			Tested at 750° C.			Tested at 1,000° C.				Coef- ficient of expan- sion 20° to 250° C.	Coef- ficient of expan- sion 20° to 600° C.	Total expan- sion in per cent of unit length	Re- sist- ance fac- tor "R"
		Modulus of—		Com- puted outer fiber strain	Modulus of—		Com- puted outer fiber strain	Modulus of—		Modulus of—		Pos- i- tivity						
		Rup- ture	Elas- ticity		Rup- ture	Elas- ticity		Rup- ture	Elas- ticity	Tan- gent modu- lus	So- cant modu- lus							
		Lbs./ in. ²	1,000 lbs./in. ²	Per cent	Lbs./ in. ²	1,000 lbs./in. ²	Per cent	Lbs./ in. ²	1,000 lbs./in. ²	Per cent	Lbs./ in. ²	1,000 lbs./in. ²	Per cent	Per cent	×10 ⁻⁶	20° to 1,000° C		
1aF	24, 37	2, 280	5, 980	0.04	580	7, 210	0.03	2, 790	4, 130	0.05	3, 500	830	42	62	26.9	(?)	3.7	
1aC	24, 37	1, 195	3, 280	0.04	595	3, 640	0.05	3, 810	2, 210	0.03	4, 450	1, 610	29	61	25.5	(?)	3.9	
2aF	24, 32	2, 180	4, 205	0.05	525	4, 890	0.05	3, 350	2, 350	0.06	2, 710	1, 120	24	30	30.3	(?)	4.1	
2aC	24, 32	1, 130	2, 340	0.05	565	3, 770	0.04	2, 655	1, 970	0.05	1, 550	785	20	51	31.0	(?)	3.6	
3aF	19, 32	1, 570	2, 520	0.06	630	5, 540	0.03	4, 400	3, 540	0.04	4, 650	470	99	127	16.2	(?)	4.7	
3aC	19, 32	1, 200	1, 960	0.06	710	5, 140	0.04	2, 440	4, 770	0.05	3, 070	230	34	177	16.2	(?)	3.3	
4aF	19, 24	1, 250	1, 730	0.07	460	3, 695	0.07	1, 740	3, 650	0.05	2, 820	23	26	35.6	(?)	(?)	2.6	
4aC	19, 24	1, 000	1, 465	0.07	490	2, 330	0.07	1, 980	2, 910	0.06	2, 940	17	26	34.3	(?)	(?)	3.3	
5aF	5, 41	1, 720	3, 220	0.05	400	3, 950	0.04	2, 110	4, 300	0.05	3, 500	830	42	62	26.9	(?)	4.4	
5aC	5, 41	955	1, 900	0.05	450	2, 300	0.04	935	2, 440	0.04	1, 610	555	29	61	25.5	(?)	3.1	
6aF	6, 25	1, 500	1, 900	0.08	400	1, 370	0.07	1, 970	3, 290	0.06	2, 710	1, 120	24	30	30.3	(?)	2.6	
6aC	6, 25	765	1, 180	0.07	490	1, 770	0.06	1, 940	1, 970	0.05	1, 550	785	20	51	31.0	(?)	3.0	
7aF	15, 42	2, 095	5, 370	0.04	550	6, 520	0.05	2, 910	5, 860	0.05	4, 650	470	99	127	16.2	(?)	4.7	
7aC	15, 42	1, 150	4, 180	0.03	565	4, 400	0.04	1, 500	3, 650	0.04	2, 775	230	34	177	16.2	(?)	3.3	
8aF	5, 16	1, 590	2, 240	0.07	400	2, 970	0.07	1, 760	2, 910	0.06	2, 900	33	26	35.6	(?)	(?)	2.6	
8aC	5, 16	1, 025	1, 430	0.07	450	2, 070	0.06	1, 700	2, 120	0.06	1, 325	17	26	34.3	(?)	(?)	3.2	
20SF	6, 25	1, 050	1, 675	0.06	460	2, 150	0.06	1, 740	2, 940	0.06	2, 080	1, 085	19	25	30.7	(?)	2.5	
21SF	10, 24	1, 455	1, 860	0.08	455	2, 310	0.08	2, 200	3, 010	0.07	3, 840	1, 055	35	8.1	59	(?)	3.4	

COMMERCIAL BODIES

		Tested at 20° C.			Tested at 750° C.			Tested at 1,000° C.			Po- res- ity	Coef- ficient of ex- pan- sion 20° to 250° C.	Coef- ficient of ex- pan- sion 20° to 600° C.	Total expan- sion in per cent of unit length	Re- sist- ance fac- tor "R"
		Modulus of—			Modulus of—			Modulus of—							
		Rup- ture	Elas- ticity	Com- puted outer fiber strain	Rup- ture	Elas- ticity	Com- puted outer fiber strain	Rup- ture	Elas- ticity	Tan- gent modu- lus					
		Lbs./ in. ²	1,000 lbs./in. ²	Per cent	Lbs./ in. ²	1,000 lbs./in. ²	Per cent	Lbs./ in. ²	1,000 lbs./in. ²	Per cent	Per cent	×10 ⁻⁶	×10 ⁻⁶	20° to 1,000° C	
A	110	1, 215	2, 890	0.04	1, 350	3, 180	0.04	1, 630	3, 880	0.04	1, 920	940	0.20	26.3	2.2
B	85	1, 200	2, 465	0.05	1, 380	2, 940	0.05	1, 620	3, 400	0.05	2, 350	1, 360	0.17	27.1	2.6
C	90	1, 415	3, 160	0.04	1, 915	2, 810	0.03	1, 150	2, 010	0.06	1, 360	1, 360	0.17	23.7	2.6
D	95	1, 415	3, 160	0.04	1, 960	2, 820	0.04	1, 150	2, 010	0.06	1, 360	1, 360	0.17	23.7	2.6
E	85	1, 415	3, 160	0.04	1, 960	2, 810	0.04	1, 150	2, 010	0.06	1, 360	1, 360	0.17	23.7	2.6
F	55	660	1, 730	0.04	1, 170	2, 480	0.07	1, 300	2, 850	0.05	1, 035	685	0.15	29.3	2.3
G	55	1, 070	2, 290	0.05	1, 055	2, 630	0.04	925	2, 980	0.02	1, 780	735	0.24	29.3	2.2
H	40	1, 750	1, 150	0.07	1, 200	2, 390	0.05	2, 200	3, 010	0.07	3, 840	1, 085	35	26.6	2.3

¹ Identification numbers of clays correspond to those used in previous reports published on this investigation.

² Values for bodies 1aF to 8aC, inclusive, were considered the same as those given in Table 2 for bodies 1F to 8C, respectively.

2. POROSITY

The porosities of the sagger bodies fired at 1,230° C. are given in Table 2 and those of the bodies fired at 1,270° C. are given in Table 3. The range in porosity, for the bodies fired at 1,230° C., is from approximately 8 to 35.5 per cent and for the bodies fired at 1,270° C. from 16 to 35.6 per cent. As shown earlier in this report, there is considerable difference in the sizes of the grog used in the preparation of coarse and fine grogged bodies. A macroscopic examination of the texture of the sagger bodies also shows a decided difference in structure of the fine and coarse grogged bodies. In practically all cases, very little difference in porosity was found for any pair of bodies of the same key number whether the grog was fine or coarse grained. Consequently, the relative pore size of the fine and coarse grogged sagger bodies was determined by measuring the rate of absorption of the bodies after complete immersion in water at room temperature for certain time intervals, namely 5 minutes, 1 hour, and 48 hours. The results given in Table 4 of the tests made on specimen bars, show great differences in porosity of bodies fired at 1,270° C.

TABLE 4.—Rate of absorption (pore size) in terms of porosity (bodies fired at 1,270° C.)

Body No.	Results obtained after immersing specimens—			Total porosity	Body No.	Results obtained after immersing specimens—			Total porosity
	5 minutes	1 hour	48 hours			5 minutes	1 hour	48 hours	
	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>		<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>
1aF-----	3.83	6.55	7.60	16.1	6aF-----	17.25	24.32	25.90	31.9
1aC-----	9.53	9.64	10.45	17.6	6aC-----	22.30	22.95	26.76	31.7
2aF-----	2.84	5.60	9.56	18.8	7aF-----	2.43	4.82	7.15	15.2
2aC-----	12.60	12.50	15.65	18.5	7aC-----	8.75	8.72	9.55	15.7
3aF-----	7.55	14.75	16.85	24.8					
3aC-----	12.63	13.91	17.95	24.5	8aF-----	20.20	27.90	29.30	34.6
4aF-----	17.54	26.25	28.17	32.4	8aC-----	26.80	26.70	28.75	33.3
4aC-----	25.03	25.32	28.00	31.3	20SF-----	18.83	24.85	27.00	31.2
5aF-----	13.98	14.32	17.12	25.6	21SF-----	16.00	27.95	29.65	33.8
5aC-----	17.25	17.08	18.52	25.1					

3. LINEAR THERMAL EXPANSION

The average coefficient of linear expansion between 20°⁷ and 250° C., 20° and 600° C., and also the total expansion at 1,000° C. in per cent of unit length are given in Table 2 for the specimens fired at 1,230° C., and in Table 3 for certain specimens fired at 1,270° C. The results obtained on the 30 bodies fired at 1,230° C. indicate that, when blending two clays and grog prepared from either one or both clays, the resulting expansion behavior of the mixture may fall into one of the three following classes:

1. It may be greater than the expansion of either clay contained in the body. In this group are included bodies Nos. 2F, 2C, 4F, 4C, 12F, and 12C.

⁷ The average room temperature was approximately 20° C. during these experiments.

2. It may be approximately equal to the average expansion of the clays making up the body. This group contains bodies Nos. 3F, 3C, 4XF, 4XC, 6F, 6C, 10F, 10C, 11F, and 11C.

3. It may be approximately the same as that of the clay in the body having the lower expansion. Bodies Nos. 1F, 1C, 5F, 5C, 7F, 7C, 8F, 8C, 9F, 9C, 13F, 13C, 14F, and 14C are in this group.

An illustration of the expansion behavior of bodies grouped in class 1 is shown on the left in Figure 1. Full line curves represent the linear thermal expansion from 20° to 1,000° C. of each of the two clays used in the preparation of bodies Nos. 4F and 4C, and broken lines those obtained on these bodies. The curves for the bodies are practically identical in this instance. Since all the bodies in class 1 contain clay No. 24, it would appear that this clay when blended with another clay and the grog made from it produces no effect on the thermal expansion of the blend fired at 1,230° C. Although bodies 4XC and 4XF have an expansion behavior similar to those grouped in class 2, the expansion curves are shown in the left section of Figure 1 to facilitate comparison with the curves for bodies 4C and 4F. Bodies 4XF and 4XC are identical in every respect with bodies Nos. 4F and 4C, respectively, except that the grog used in the former had been fired to approximately 775° C. instead of 1,230° C. Due to the comparative softness of the grog fired at 775° C., it disintegrated somewhat during mixing with the clays and pugging of the body which caused a more intimate mixture of clays and grog than if the grog had been fired at a considerably higher temperature. This, together with the fact that the clay as grog had not altered as much in its physical properties when fired at 775° C. as when fired at 1,230° C., probably was the cause of a more complete reaction occurring between the constituents in the clay and grog which resulted in an expansion approximately the average of the two individual clays.

An example of the expansion of bodies grouped in class 2 is shown in the center section of Figure 1. The curves given were obtained on bodies 10F and 10C which were prepared from clays Nos. 5 and 6 and grog made from these clays. The expansion curves for the individual clays are also shown.

To the right in Figure 1 are given the expansion curves of bodies 14F and 14C, which are included in class 3. These bodies were made of clays Nos. 18 and 49, and grog from the same clays fired at 1,230° C. The thermal expansion curves for the individual clays, also given, show a large difference in total expansion. Since the expansions of the bodies closely approach the lower and more desirable expansion of clay No. 18, it would indicate that the selection of clays as far as this property is concerned was favorably made. Apparently most clays blended as in this study act favorably with respect

FIGURE 1.—Thermal expansion curves of representative clays and of bodies prepared from them

The curves illustrate the various changes which may occur in the thermal expansion when clays are blended

to the thermal expansion since the majority of bodies are classed in this group.

Table 1 shows that all bodies except Nos. 11F and 11C were prepared from clays having the same general type of expansion; that is, both were classed in either group H or L. Bodies Nos. 11F and 11C were prepared with clay No. 35 from group H (uniform and relatively low rate of expansion below 200° C.) and clay No. 41 from group L (irregular and relatively higher rate of expansion below 200° C.). Figure 2 shows the expansion curves for bodies

FIGURE 2.—Showing widely different types of thermal expansion curves of two clays (full lines) and of the two bodies in which they were blended

Nos. 11F and 11C as well as those of clays Nos. 35 and 41. The expansion curves of the bodies illustrate what may be accomplished by blending two clays having a very large difference in total expansion as well as entirely different rates of expansion below 200° C. The P. C. E. values of clays Nos. 35 and 41 are 20–26 and 30–31, respectively. Any reaction occurring between these clays during firing was undoubtedly facilitated by the comparatively low P. C. E. value of clay No. 35. The combination of these two clays was decidedly advantageous in eliminating the high and unfavorable rate of expansion of clay No. 41 below 200° C.

A comparison of the thermal expansion curves of the bodies

containing the coarser grog with those prepared with the finer grog shows that the expansion of the coarse-grogged bodies is slightly lower than the fine-grogged bodies in 67 per cent of those tested, approximately the same in 20 per cent, and higher in 13 per cent.

A comparison of the thermal expansion curves of the sagger bodies with those of the two clays composing each of the bodies shows that out of the total of 15 combinations, 12 were advantageously made with respect to the thermal expansion of either one or both clays.

Check determinations of expansions were made on eight specimens of sagger bodies. The greatest variation in the data obtained on the same body was less than $\pm 2\frac{1}{2}$ per cent.

4. MODULUS OF ELASTICITY AND TRANSVERSE STRENGTH

The deflections corresponding to various loads applied to body 20SF are plotted in Figure 3. Results obtained at 20, 460 (the temperature at which the sagger failed in the heat shock test), and 750° C. are plotted to illustrate the increase in resistance to bending of sagger bodies as the temperature within these limits is increased.

Bodies fired at 1,230° C.—The modulus of elasticity and transverse breaking strength (modulus of rupture) of 37 bodies, including 8 containing the grog fired at 775° C. and 1 containing grog and dust passing through a No. 80 sieve, were determined at room temperature, at the temperature of failure in an air-quenching test of saggars

FIGURE 3.—Curves showing the typical stress (load) strain (deformation) relation of a sagger body tested at three temperatures

made from these bodies and at 750° C. The values obtained on 1 by 1 by 12 inch specimens, using a 10-inch span are given in Table 2.

Bodies fired at 1,270° C.—The modulus of elasticity and transverse breaking strength of 18 bodies, including 2 containing special graded grog sizes, and in addition 8 commercial bodies fired at 1,270° C. are given in Table 3. These bodies were tested at 1,000° C. in addition to the three temperatures specified for bodies fired at 1,230° C. The composition and order of arrangement of the first 16 bodies in Table 2 are identical with the first 16 bodies in Table 3.

The results indicate that there is a slight tendency for the bodies to show increased transverse breaking strength with increased tem-

peratures to 1,000° C., the maximum temperature used in these tests. The same holds true regarding the modulus of elasticity up to 750° C. At 1,000° C. the latter property shows a decided decrease. The percentage increase in the modulus of elasticity attending an increase in temperature from 20 to 750° C. is greater than the corresponding increase in cross-breaking strength. Figure 4 shows the effect of temperature on the modulus of elasticity of bodies fired at 1,270° C. The curves are presented in three sections to facilitate examination.

Values for the modulus of rupture determined at approximately 20° C. for bodies fired at 1,230° and 1,270° C. and plotted as in Figure 5 indicate that the ordinary or usual relation exists between transverse strength and modulus of elasticity; that is, the modulus of elasticity is greatest with the greatest strength. These figures also show that the modulus of elasticity increased more rapidly than the modulus of rupture as the temperature of firing was raised. As stated in Report III,⁸ the relationship is only approximate and the explanation for the variations is not evident from the data at hand.

TABLE 5.—*Determinations and checks of moduli of elasticity and rupture obtained on sagger bodies at several temperatures*

Body No.	Modulus of elasticity	Modulus of rupture	Results obtained at—
	<i>1,000 lbs./in.²</i>	<i>Lbs./in.²</i>	
4XC-----	{ 1,730 1,740	{ 1,210 1,215	Room temperature.
8C-----	{ 1,000 1,110	{ 510 500	
10C-----	{ 520 565	{ 450 395	
11C-----	{ 1,340 1,625	{ 660 600	
3F-----	{ 3,920 3,500	{ 1,770 1,940	
5F-----	{ 3,520 3,560	{ 1,970 1,920	Temperature at which sagger failed in heat shock test.
6C-----	{ 1,960 1,960	{ 950 920	
7C-----	{ 3,050 3,330	{ 1,185 1,355	
9C-----	{ 4,400 4,285	{ 1,200 1,340	
9F-----	{ 5,920 6,020	{ (^a) 2,320	
13F-----	{ 3,100 3,100	{ (^a) 2,320	750° C.
6aC-----	{ 1,180 1,200	{ 765 760	Room temperature.
6aC-----	{ 785 700	{ 1,550 1,420	
			1,000° C.

^a No data obtained.

⁸ See footnote 1, p. 420.

FIGURE 4.—Effect of temperature on the modulus of elasticity of 18 sagger bodies

Filled circles indicate temperatures at which sagers failed in the air-quenching test

FIGURE 5.—Showing the relation between modulus of elasticity and transverse strength (modulus of rupture) determined at room temperature of sagger bodies fired at either 1,230° or 1,270° C.

The third progress report of this investigation states that check determinations of moduli of elasticity and rupture were made at room temperature on all clay specimens and check determinations were made of three clay specimens at higher temperature. The results varied less than 10 per cent. Check determinations of these same properties were made on 25 specimens referred to in the present report and a number of these values, together with the original determinations, are given in Table 5 to illustrate the variation in results. The results in the majority of these cases also varied less than 10 per cent. The test piece was considered defective if the

FIGURE 6.—Showing the load-deflection curves of body 20SF at 1,000° C.

The upper curve shows the plastic flow or set of the material, the middle curve the elastic deflection, and the lower curve the total deflection at each of the loads indicated

rupture occurred at a point other than at approximately the middle of the 10-inch span. In such cases the necessary data were determined on a second specimen. As has been stated, those specimens of each body tested at three temperatures not greater than 750° C., exclusive of the test at 1,000° C., were found to have decreased in flexibility as the temperature was raised at which the tests were made. If the load-deflection curves for these specimens became more nearly vertical with each increase of temperature (thus indicating a decrease in flexibility) this fact was considered as further evidence of the specimens being free from important defects.

5. PLASTIC FLOW

Typical load deflection curves, as obtained at 1,000° C. for body No. 20SF are shown in Figure 6. The upper curve shows the plastic flow of the material under various loads, the center curve shows the elastic properties, and the lower curve shows the total deflection of the specimen at each of the loads indicated. As stated in Report IV,⁹ the elastic recovery of the material was considered as the difference between the deflection caused by the load and the "set" of the material on removal of this load. The deflections resulting from plastic flow of 24 sagger bodies fired at 1,270° C. are given in columns 2 and 3, Table 6. The results were obtained at 1,000° C. and they are the average of increments obtained every five minutes for one-half hour when using a load of 30 lbs./in.², and for one hour when using a load of approximately 120 lbs./in.². The load was applied midspan of the 1 by 1 by 12 inch specimens on a 10-inch span. The

FIGURE 7.—Effect of porosity on the plastic flow of sagger bodies

values given in column 4, Table 6, represent the total plastic deflection, in inches, of the various bodies under a stress of approximately 240 lbs./in.². The values, taken from curves similar to that identified as "plastic" in Figure 6, illustrate the large variation in this property among the various bodies. It is quite possible that an appreciable error may be present in the results obtained with a load of 30 lbs./in.² because of the limit of accuracy of the apparatus used.

For convenience the porosities of the bodies fired at 1,270° C. are shown in column 5, Table 6, with the plastic-flow data. These values plotted in Figure 7 indicate that, as illustrated by one of a number of lines which may be drawn through the plotted points, there may be a tendency for the plastic flow (column 4) of the body to decrease as the porosity of the body becomes greater when determined under the conditions stated.¹⁰ Such a relation might be expected, since the

⁹ See footnote 1, p. 420.

¹⁰ This relationship would possibly become more exact if deflection determinations had been made on several specimens instead of only one, as in the present study. The porosity given is the average of five determinations.

fluxes introduced by the clays in a dense sagger body have a greater opportunity for reaction during firing than if present in a less dense body.

TABLE 6.—*Plastic flow data determined on sagger bodies fired at 1,270° C.*

Body No.	Average of deflection readings, in inches, taken at 5-minute intervals, on a 1 by 1 by 12 inch specimen, using a 10-inch span and temperature of 1,000° C.		Total plastic deflection, in inches (taken from plastic flow curves), at 1,000° C. with a stress approximately 240 lbs./in. ²	Porosity
	During one-half hour, using stress approximately 30 lbs./in. ²	During 1 hour, using stress approximately 120 lbs./in. ²		
1	2	3	4	5
				<i>Per cent</i>
1aF.....	0.0002	0.0002	0.012	18.1
1aC.....	.0002	.0003	.016	16.9
2aF.....	<.0001	<.0001	.006	20.3
2aC.....	<.0001	.0001	.010	21.7
3aF.....	<.0001	<.0001	.007	23.6
3aC.....	<.0001	.0001	.008	22.9
4aF.....	<.0001	<.0001	.003	32.6
4aC.....	<.0001	<.0001	.005	32.1
5aF.....	.0001	.0002	.017	26.9
5aC.....	.0002	.0003	.017	25.5
6aF.....	.0001	.0001	.005	30.3
6aC.....	.0001	.0001	.005	31.0
7aF.....	.0002	.0004	.025	16.2
7aC.....	.0002	.0007	.053	16.2
8aF.....	<.0001	<.0001	.004	35.6
8aC.....	.0001	.0001	.006	34.3
20SF.....	<.0001	<.0001	.004	30.7
21SF.....	<.0001	.0001	.004	33.3
A.....	.0001	.0001	.012	26.3
B.....	.0001	.0001	.004	27.1
E.....	.0001	.0001	.011	29.9
F.....	.0001	.0001	.018	29.3
G.....	.0001	.0001	.016	29.9
H.....	.0001	.0002	.011	26.6

Bodies 7aF and 7aC, although showing good resistance in the heat-shock test, would undoubtedly prove unsatisfactory for sagger purposes because of a comparatively high plastic flow at 1,000° C.

6. AIR QUENCHING OR DUNTING TESTS

The results, showing the average temperature of failure of five small oval saggars in the heat-shock test, are given in Table 2 for the saggars fired at 1,230° C. and in Table 3 for the saggars fired at 1,270° C. Table 3 also contains the results of the tests on saggars prepared from commercial sagger bodies furnished by several potteries.

FIGURE 8.—*Saggers illustrating the three types of failures which occurred in the thermal shock test*

The types of failure encountered during the testing of these saggars are shown in Figure 8. Sagger No. 1 illustrates a failure found only in saggars prepared from bodies containing the fine grog sizes. Sagger No. 2 shows the type of failure which was the most prevalent. The third type of failure, illustrated by sagger No. 3, occurred only in a few cases.

The average, the maximum, and the minimum temperatures of failure and porosities of the saggars prepared from the first 16 bodies listed in Tables 2 and 3 are as follows:

	Temperature of failure of saggars fired at—			
	1,230° C.		1,270° C.	
	Fine grog	Coarse grog	Fine grog	Coarse grog
Maximum.....° C.	760	860	400	450
Minimum.....do.	415	500	630	710
Average.....do.	580	675	495	540
Porosity.....per cent.	26.2	26.2	25.4	25.1

These average values show that the coarse-grogged saggars resist thermal shock to a considerably greater extent than the fine-grogged saggars, although this difference is more pronounced in the saggars fired at 1,230° C. than those fired at 1,270° C. These results also show that the resistance to thermal shock decreases noticeably with the increased temperature of firing of saggars. Furthermore, a comparison of the average porosities of the fine and coarse grogged bodies indicates that, within the ranges of grog sizes and temperatures of firing studied, the porosity as determined does not give a true indication of the pore structure of the body.

Sagger bodies Nos. 9F, 9C, 10F, 10C, 12F, 12C, 13F, and 13C were prepared from two clays each and grog made from only one of the clays used in the respective bodies. The grog used in sagger mixes 9F, 9C, 12C, and 12F was prepared from that clay in the mix having the lower porosity after firing at 1,230° C., whereas bodies 10F, 10C, 13F, and 13C contained grog prepared from that clay in the body having the higher porosity after firing at 1,230° C. Furthermore, bodies Nos. 7F and 7C contain the same clays as 9F and 9C and bodies 13F and 13C contain the same clays as 14F and 14C. The results obtained in the thermal shock test indicate that saggars prepared with grog having a relatively high porosity show greater resistance to heat shock than do saggars containing grog having a low porosity. A summary of the average values obtained on the fine and coarse grogged bodies as well as those of the clays are as follows:

Average temperature of failure of saggars

Body Nos.	Type of grog in body	Prepared from—		Remarks
		Single clays	Blended clays	
7F and 7C	Equal parts high and low porosity	° C. 665	° C. 650	} Same clays in bodies 7 and 9.
9F and 9C	Low porosity	665	605	
10F and 10C	High porosity	390	520	
12F and 12C	Low porosity	570	575	} Same clays in bodies 13 and 14.
13F and 13C	High porosity	435	655	
14F and 14C	Equal parts high and low porosity	435	575	

Bodies Nos. 10 and 12, although compounded with different clays, illustrate the effect on the resistance to thermal shock of saggars containing either dense or porous grog. As shown, the average of the two failing temperatures of the saggars made from each clay used in body No. 10 was 390° C.; the saggars from the blended clays and a porous grog showed greatly increased resistance to failure. The temperature of failure in this case was 520° C. In the case of body No. 12 the average of the two failing temperatures of the saggars prepared from each clay was 570° C., whereas the average of the failing temperatures of saggars prepared from the blended clays and a dense grog was 575° C. Furthermore a comparison of the results obtained on body No. 7 with body No. 9 and also on body No. 13 with body No. 14 indicates that the sagger containing the greater percentage of porous grog shows the greatest resistance to heat shock.

Body No. 11F and body No. 11C are described in the section on "Linear thermal expansion." The average of the two failing temperatures of the saggars made from each of the constituent clays was 465° C., the average of the two failing temperatures of saggars prepared from the blended clays was 645° C. The reaction which occurred, incident to the burning of these two blended clays caused an unusual improvement in the thermal expansion of the blended clay sagger bodies (see fig. 2) and undoubtedly was partially the cause of the excellent resistance to failure shown by the saggars in the heat-shock test.

Bodies Nos. 1XF to 4XC, inclusive, representing the eight sagger mixes compounded with grog materials burned at 775° C. contain clays of the same laboratory key numbers as bodies Nos. 5, 6, 7, and 4, respectively. As indicated by the results in Table 2, this method of preparing grog does not improve the resistance of saggars to thermal shock. The grog is sufficiently soft to permit its disintegration during pugging of the sagger body which, in consequence, causes a body of finer texture with increased modulus of elasticity. At the same time the heat conductivity of the sagger is probably decreased, which also would be a factor in decreasing the resistance to failure in the heat-shock test.

Body 15S, which contains the grog and dust passing an 80-mesh sieve, was included to show the effect of extremely fine grog on the resistance to failure of a sagger in the thermal shock test. Both the porosity and transverse strength of this body are high, and the sagggers failed at or below 350° C., an exceptionally low temperature. Body No. 8F containing the same body composition, but with graded grog, failed at 450° C.

Body 21SF (Table 3) was prepared from the same clays as bodies Nos. 4aF and 4aC, but the grading of the grog was varied as shown in the section on "Sagger body compositions." Although body 21SF contained 40 per cent of grog passing an 80 and retained on a 200-mesh sieve, the sagger failed in the air-quenching test at approximately the same temperature as body 4aF which contained no grog finer than that retained on an 80-mesh sieve. This would indicate that properly graded grog sizes, even as fine as those used in body 21SF, may be used to advantage to increase the mechanical strength of sagggers.

Body No. 20SF was prepared from the same clays as bodies Nos. 6aF and 6aC, but with a fairly wide range of specially graded grog sizes. The sagggers made from body 20SF failed at 460° C. in the heat-shock test, the approximate average failing temperature of sagggers made from bodies 6aF and 6aC which failed at 400° and 590° C., respectively. The modulus of elasticity and transverse strength of body 20SF determined at 20° C. is also approximately the average of that obtained on bodies 6aF and 6aC. According to the data given in Table 6, the plastic flow of body 20SF under a load of 240 lbs./in.² is slightly less than that of either body 6aF or 6aC. It would, therefore, appear from the limited data available that the use of grog, graded into as many as six sizes, is of no outstanding advantage in a sagger body when compared with bodies using three sizes of graded grog.

The data show that the individual sagggers in any one set of five fired at 1,230° C. failed in the quenching test within 100° C. or less of one another in 32 out of a total of 37 bodies, and those fired at 1,270° C. failed within 75° C., or less, of one another in 23 out of a total of 26 bodies.

7. RELATION BETWEEN POROSITY AND DUNTING

As indicated by the following table of averages of temperatures at which sagggers failed in the air-quenching test and the porosities of the fired sagger bodies, it is advantageous to keep the porosities of these bodies below 25 per cent. The bodies were separated into two

groups, according to whether the porosity was greater or less than 25 per cent:

Saggers fired at—	Average temperature of failure	Porosity
$^{\circ}\text{C.}$ 1,230	$^{\circ}\text{C.}$ 675	Per cent 20.7
1,270	565	31.2
	590	19.5
	455	31.2

Sufficient data are not at hand to warrant any conclusions as to the lowest permissible porosity compatible with the longest sagger life.

8. EFFECT OF THERMAL EXPANSION ON DUNTING

Grouping the sagger bodies fired at $1,230^{\circ}\text{C.}$ into two classes according to whether saggers prepared from them failed at temperatures above or below 600°C. and averaging the temperatures at which they failed as well as the coefficients of expansion of each group from 20 to 250°C. gives the following:

Group	Average failing temperature	Average coefficient of expansion
I-----	$^{\circ}\text{C.}$ 695	$\times 10^{-6}$ 6.1
II-----	525	8.2

9. MODULUS OF ELASTICITY, EXPANSION, TRANSVERSE STRENGTH, POROSITY, AND RESISTANCE TO DUNTING

An empirical relation, combining the three factors (1) modulus of elasticity, (2) linear thermal expansion, and (3) transverse strength, which was suggested as indicating the relative resistance to failure due to thermal shock, was given in Report III.¹¹ The sagger bodies referred to in that report contained grog which had been graded alike for all mixtures. Substituting the data obtained in the present work in that formula, it was found that the factors R so computed did not satisfactorily indicate the relative resistance to thermal shock actually obtained. Changing the formula to include the porosity of the body overcame this discrepancy. This may be from the fact that the thermal conductivity of the body probably has a significant effect on its resistance to heat shock. Since it is reasonable to assume that pores affect conductivity, porosity might be introduced into the for-

¹¹ See footnote 1, p. 420.

mula and more consistent values of R obtained. Consequently the formula is altered as follows:

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

where
 R = factor indicating relative resistance of a sagger to failure,
 M = modulus of rupture,
 E = modulus of elasticity,
 e = coefficient of linear thermal expansion,
 P = porosity.

FIGURE 9.—Showing the resistance (R) of saggers, fired at either 1,230° or 1,270° C., to dunting

Data used in computing the resistance factor were determined at 20° C., and the average coefficient of expansion was taken from 20° C. to the temperature at which the saggers failed in the air-quenching test

The resistance factors R , computed from the moduli of elasticity and rupture and porosity determined at 20° C. and the average coefficient of expansion for the range from 20° C. to the temperature at which the saggers failed in the heat shock test, are given in Tables 2 and 3 for the saggers fired at 1,230 and 1,270° C., respectively. R plotted against the failing temperature of the saggers in Figure 9 shows, in general, that the greater the numerical value of this factor the greater the resistance of the sagger body to heat shock. Values for R computed from the moduli of elasticity and rupture determined

at either 750° C. or the failing temperatures of the saggars in the heat-shock test and the average coefficient of expansion between 20 and 600° C. give a similar relation. Although the relation between the calculated resistance R and the life of the sagger as indicated by the quenching test is not as close as may be desired, the trend of the points in Figure 9 indicates such a relation. The irregularities in the trend of the points may be partially accounted for by the differences in fired properties resulting from unavoidable variations in the heat treatment which the saggars and specimen bars received. This difference in heat treatment was especially apparent in the case of the material fired at 1,230° C., the resistance factors for which show the greater irregularity. In addition, other properties, such as thermal conductivity and modulus of elasticity in shear, which have not been determined in these studies, undoubtedly have an appreciable effect on the resistance of saggars to failure in the thermal shock test.

The resistance factors for the majority of the bodies fired at 1,230° C. are grouped near the approximate center of the upper graph in Figure 9, whereas the bodies fired at 1,270° C. have grouped themselves to the bottom left of the lower graph. This illustrates that the firing at the higher temperature has a detrimental effect on the resistance of the sagger to heat shock. Since repeated firings at the same temperature appear to have similar effects on the properties of sagger bodies¹² as firing at higher temperatures, it would appear that the resistance of a sagger to heat shock is decreased after each heating cycle in service. In the lower graph the factor for body 7aF is an exception to the general trend for bodies in that group. The factor indicates a relatively high resistance while the temperature at which the saggars failed is comparatively low.

10. EXTREME FIBER DEFORMATION

The maximum deformation of the extreme fiber¹³ is the deformation under the maximum stress at mid span along the upper and lower surfaces of the specimen. The outer fiber deformation values of the fired sagger bodies at various temperatures given in Tables 2 and 3 (columns headed "Computed outer fiber strain") are all computed by the following formula:

$$\left. \begin{array}{l} \text{Maximum elongation per} \\ \text{unit length, per cent} \end{array} \right\} = \frac{\text{modulus of rupture}}{\text{modulus of elasticity}} \times 100$$

The values so obtained are an expression of the approximate flexibility of the materials. An examination of these data indicates that the flexibility of the bodies decreased (1) with increased temperature

¹² Data on the effect of repeated firing of sagger clays are published in Report I. See footnote 1, p. 420.

¹³ A detailed discussion on maximum deformation (elongation) and why it is desirable to use the secant modulus of elasticity when computing the strain values at 1,000° C. may be found in Report IV of this investigation. See footnote 1, p. 420.

of firing and (2) as the temperature of the material is raised until plastic flow commences under the load applied.

11. COMMERCIAL SAGGER BODIES

The laboratory identification letters for the commercial sagger mixes are A to H, inclusive. The properties of the bodies as determined on specimen bars and experimental saggars fired at 1,270° C. (cone 11½-12) are given in Table 3. The resistance factors R , of these mixes, given in Table 3, are included with the others plotted in Figure 9. The resistance to failure in the thermal shock test of saggars, prepared from bodies C, E, and H, is noticeably greater than that of the saggars prepared from the other five bodies. The modulus of elasticity of each of these three bodies is less and the computed outer fiber strain is greater than those of the remaining bodies. The increased resistance to failure of the saggars made from these bodies is probably due to these favorable factors. The properties of these bodies appear as a whole to be similar to the properties of the coarse grogged experimental bodies prepared in the laboratory. Largely, because of the coarse sizes of grog used in the bodies, the fired strength and the modulus of elasticity are low. It is believed that a low modulus of elasticity is desirable in a sagger body.

Bodies C and D were furnished by the same manufacturer. Body C, developed after a study of experimental sagger bodies, shows a great improvement in resistance to thermal shock when compared with body D. The modulus of elasticity of body D is approximately twice that of body C and is probably one of the most significant properties affecting dunting of saggars in the heat shock test at comparatively low temperatures. These data are of especial interest since they demonstrate that increased life of saggars, due to their greater resistance to thermal shock, may be obtained by altering the sagger mixes in such a manner as to produce a structure of the fired ware having those properties effective in prolonging the life.

VI. SUMMARY

Five small saggars were made from each of 23 experimental bodies and 10 small saggars were made from each of 16 bodies. The 39 bodies were prepared from 15 different clays and grogs made from these clays. The majority of the bodies were made of two clays and grogs prepared from these clays, each combination of clays being made into two bodies, one prepared with coarse-graded grog and the other with comparatively fine-graded grog. The saggars were tested for resistance to heat shock after firing at either 1,230° or 1,270° C. Specimen bars were made to correspond with each set of saggars and fired simultaneously with the saggars. These bars were used for determining the linear thermal expansion from 20° to 1,000° C., porosity,

moduli of elasticity, and rupture at room and elevated temperatures, and plastic flow at $1,000^{\circ}\text{C}$. In addition, saggars and specimens from eight raw sagger bodies furnished by potteries were fired at $1,270^{\circ}\text{C}$. and tested.

The linear thermal expansion of the bodies fired at $1,230^{\circ}\text{C}$. shows that they may be classed as follows into three groups according to the expansion: That of the body may be (1) greater than that of either clay, (2) approximately equal to the average of that of the clays, (3) approximately equal to the clay having the lower expansion. A comparison of the expansion of the bodies prepared with the coarse sizes of grog against those prepared with the finer sizes of grog shows that in the majority of cases the coarse-grogged bodies have the lower expansion. A comparison of the thermal expansion of the sagger bodies with those of the clays contained in the bodies shows that of the total of 15 combinations, 12 had more desirable expansions than either one or both of the constituent clays.

A direct relation between modulus of elasticity and transverse strength of the bodies is shown. The modulus of elasticity increased more rapidly than the strength when the bodies were (a) fired at $1,270^{\circ}\text{C}$. as compared with $1,230^{\circ}\text{C}$., and (b) tested at increasing temperatures ranging from 20° to 750°C .

A relation between porosity and plastic flow of the bodies under load at $1,000^{\circ}\text{C}$. is indicated.

The results show that the resistance of saggars to thermal shock (1) decreases with increased temperature of firing of saggars, (2) is generally less for bodies having a porosity greater than 25 per cent when compared with those having a porosity less than 25 per cent, (3) is greater for saggars prepared with grog having a relatively high porosity than those containing grog of low porosity, and (4) is greater for bodies having a comparatively small and uniform rate of expansion below 250°C .

A study of the data indicates that the best sagger bodies found in this preliminary experimental study are those having the following properties: (1) Low modulus of elasticity, (2) high transverse strength, (3) porosity below 25 per cent, and (4) low and preferably uniform thermal expansion from 20° to 250°C . In addition, it was found that clays of low refractoriness may sparingly and advantageously be used to increase sagger life and that properties stated as (1) and (2) may be partially controlled by grading of grog sizes.

The modulus of elasticity, transverse strength, porosity and coefficient of expansion may be combined into an empirical formula which will give indications of the probable life of a sagger when subjected to repeated thermal shock.

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