THE LIFE OF THE SAGGER AS AFFECTED BY VARYING CERTAIN PROPERTIES

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ABSTRACT

This report presents the results obtained in a study of sagger bodies and represents an enlargement of a similar study of a preliminary nature, the results of which have been published. The clays and grogs are combined to give bodies having wide variations in body structure and in the several properties which were studied. Data are given on the modulus of elasticity, transverse breaking strength, plastic flow, thermal expansion, and resistance to failure due to heat shock of 35 laboratory-prepared bodies and 10 commercial bodies after firing at from 1 to 3 different temperatures. For comparative purposes data are given on two series of bodies—the one series containing coarse grog and the other fine grog. In addition, body compositions were varied in order to compare the effect on sagger life of using open and close burning grogs.

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I. INTRODUCTION

The investigation of the properties of sagger clays and sagger bodies has been in progress at the Bureau of Standards for a number of years, and as the study has progressed reports[1] have been issued covering the completed phases. Since the results given in the preceding report were of a preliminary nature, it was considered advisable to continue the study of sagger bodies with special reference to the effect of porosity, thermal expansion, and moduli of rupture and elasticity on the resistance of saggers to failure due to thermal shock. This paper contains the results of tests made on 35 different laboratory-prepared sagger bodies as well as on 10 sagger bodies furnished by industrial potteries, all of which were fired at from one to three different temperatures.

[1] Progress Report on Investigation of Sagger Clays, J. Am. Ceram. Soc., vol. 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., vol. 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., vol. 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., vol. 10 (12), pp. 995–1004; 1927. Preparation of Experimental Sagger Bodies According to Fundamental Properties, B. S. Jour. Research, vol. 3 (RP104); also J. Am. Ceram. Soc., vol. 12 (7), pp. 457–480; 1929.

II. SAGGER BODY COMPOSITIONS

All of the bodies contained equals parts by weight of bond clay and grog, but variations in the bond clay and grog were introduced by using different combinations of clays and of grogs in several of the mixes. The grogs used were fired at approximately 1,230° C. (cones 9 to 9½) for one and one-half hours. The sagger body numbers, the laboratory numbers of the clays used as bond and as grog and the percentages of each used in making up the various bodies are given in Table 1.

TABLE 1.—*Sagger body numbers, and composition of bodies and prorosity of fired clay*

(Table does not include bodies furnished by potteries)

Sagger body No.[1]	Laboratory No. of bond clays	Percentage of each clay used	Laboratory No. of grog clays	Percentage of each grog used
1BF, 1BC [2]	21, 47	50	15, 42	50
2BC	21, 47	50	19, 24	50
3BF	21, 50	50	19, 24	50
4BF, 4BC	10, 40	50	5, 41	50
5BF, 5BC	26 51	75 25	26, 51	50
6BF, 6BC	19, 26, 51	33⅓	26, 51	50
7BF, 7BC	22 46	40 60	28, 36	50
8BF, 8BC	11 28 50	25 25 50	9, 43	50
9BF, 9BC	43, 44	50	43, 44	50
10BF, 10BC	8, 45	50	8, 45	50
11BF, 11BC	8, 45	50	45	100
12BF, 12BC	8, 45	50	8	100
13BF, 13BC	22 29	40 60	1, 12	50
14BF, 14BC	39, 44, 45	33⅓	2, 4	50
15BF, 15BC	21, 46	50	21, 46	50
16BF, 16BC	21, 46	50	21	100
17BF, 17BC	21, 46	50	46	100
18BC	(3)	100	22, 39	50
19BC	(3)	100	22	100
20BC	(3)	100	39	100

[1] Bodies containing the fine grog are designated F, those containing the coarse grog, C. The letter B is used with the body number to differentiate these bodies from those in the preceding reports.
[2] Bodies 1BF to 4BC, inclusive, contained grog prepared from saggers used for tests referred to in the preceding report (see footnote 6) and may be identified by the numbers of the grog clays. The remaining bodies contained grog prepared from clays independently fired and afterwards mixed in the proper proportions.
[3] Commercial mix.

The majority of the bodies were prepared, as in previous work, in two series. 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.

The grog sizing and the percentages of each size were as follows:

Material	Passed through sieve No. —[1]	Retained on sieve No. —[1]	Percentage of each size
For coarse grogged body	4 8 12	8 12 20	20 60 20
For fine grogged body	20 40	40 80	66⅔ 33⅓

[1] United States standard series.

Five bodies were prepared using dense and open burning grogs and a commercially prepared mixture of sagger clays.

III. DESCRIPTION OF SPECIMENS

The specimens were prepared and tested in a manner similar to that described in the Fifth Progress Report.[2] In order to obtain a gradational change in the porosity and other physical properties, a large proportion of the saggers and specimen bodies were fired at three different temperatures, namely, approximately 1,190° C. (cones 7½ to 8); 1,230° C. (cones 9½ to 10); 1,270° C. (cones 11 to 12).

IV. METHODS OF TESTING

The methods of determining the modulus of rupture, porosity, resistance to thermal shock, linear thermal expansion, modulus of elasticity, and plastic flow have been described in detail in the several previous progress reports.[3]

V. RESULTS

The complete results obtained are summarized in Table 2. The body numbers are followed directly by the number of the pyrometric cone to which the particular saggers and specimen bars were fired.

1. MODULUS OF RUPTURE AND SHRINKAGE, UNFIRED BODIES

The average modulus of rupture for the laboratory-prepared bodies which contained the fine grog was 155 lbs./in.^{2}, for bodies which contained the coarse grog 115 lbs./in.^{2}, and for commercial bodies 80 lbs./in.^{2}

The average linear drying shrinkage for the fine-grogged bodies was 4.2 per cent, the coarse-grogged bodies 3.0 per cent, and the commercial bodies 3.4 per cent.

2. PROPERTIES OF THE BODIES AFTER FIRING

The porosities of the bar specimens as well as those of the saggers are given in Table 2. Each of the values represents the average of not less than three determinations.

The total linear thermal expansion for the ranges from atmospheric temperature to 250° C. and from atmospheric temperature to 1,000° C., as well as the coefficient for the former range are given. The determinations were made on specimens prepared from the ruptured bars used for the strength and elasticity tests. Duplicate determinations were made on all specimens.

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[2] See last reference of footnote 1, p. 1017.

[3] See footnote 1, p. 1017.

TABLE 2.—*Properties of sagger bodies*

Body No. and cone at which fired	Modulus of rupture of unfired body	Dry shrinkage	Fired shrinkage	Tested at 20° C.			Tested at temperature at which sagger failed in quenching test				Tested at 1,000° C.		Total plastic deflection in inches (taken from plastic flow curves). Stress of approximately—		Porosity of bars	Porosity of saggers	Total expansion from atmospheric temperature to 250° C.	Coefficient of expansion atmospheric temperature to 250° C.	Total expansion from atmospheric temperature to 1,000° C
				Modulus of—		Computed[1] outer fiber strain	Modulus of—		Computed[1] outer fiber strain	Sagger[2] failing at	Modulus of—								
				Rupture	Elasticity		Rupture	Elasticity			Rupture	Elasticity	120 lbs./in.²	240 lbs./in.²					
	Lbs./in.²	*Per cent*	*Per cent*	*Lbs./in.²*	*1,000 lbs./in.²*	*Per cent*	*Lbs./in.²*	*1,000 lbs./in.²*	*Per cent*	*°C.*	*Lbs./in.²*	*1,000 lbs./in.²*	*×10⁻⁴*	*×10⁻⁴*	*Per cent*	*Per cent*	*Per cent*	*×10⁻⁶*	*Per cent*
1BF-8+	180	4.3	1.5	1,720	3,370	0.051	1,785	4,050	0.044	565	2,260	450	9	33	27.2	26.6	0.12	5.4	0.52
1BF-10+	180	4.3	2.1	1,725	3,800	.045	1,570	3,720	.042	540	1,910	455	12	33	24.0	21.7	.11	5.1	.50
1BF-12	180	4.3	2.4	2,095	5,380	.039	1,960	5,440	.036	525	2,710	555	9	21	20.0	19.2	.11	4.7	.47
1BC-8+	130	3.5	1.0	955	2,100	.045	------	------	------	635	1,010	295	14	52	27.2	26.3	.13	5.7	.53
1BC-10+	130	3.5	1.4	995	2,305	.043	900	3,140	.029	610	1,255	325	14	50	25.0	21.6	.11	5.0	.49
1BC-12	130	3.5	2.7	1,130	3,095	.036	1,250	3,670	.034	585	1,650	365	85	35	21.0	21.9	.11	4.8	.50
2BC-8+	105	2.7	1.7	480	715	.067	860	1,335	.064	865	780	300	12	49	37.0	37.8	.14	6.3	.55
2BC-10+	105	2.7	2.2	470	755	.062	725	1,235	.059	860	825	305	10	47	35.3	31.2	.13	5.7	.52
2BC-11+	105	2.7	2.6	495	930	.053	695	1,515	.046	775	900	320	6	42	32.4	32.0	.13	5.7	.49
3BF-8+	130	4.5	.9	695	990	.070	1,115	2,165	.051	690	1,055	475	7	25	36.4	35.8	.13	5.8	.53
3BF-10+	130	4.5	1.3	815	1,140	.071	870	2,190	.040	635	1,340	545	5	15	34.4	32.3	.15	6.4	.54
3BF-11+	130	4.5	1.8	1,095	1,565	.070	1,200	2,300	.052	610	1,630	695	4	13	32.8	32.4	.16	7.0	.54
4BF-8+	165	4.1	1.6	1,345	2,070	.065	1,635	2,495	.065	415	1,840	730	5	10	30.0	29.2	.23	10.0	.67
4BF-10+	165	4.1	2.0	1,395	2,295	.061	1,570	2,660	.059	410	2,000	860	3	9	29.3	26.6	.23	10.2	.62
4BF-12	165	4.1	2.8	1,735	2,930	.059	1,915	3,690	.052	390	2,810	1,520	1	4	26.5	26.5	.25	11.0	.67
4BC-8+	95	2.8	1.8	770	1,240	.062	830	1,685	.049	450	930	475	6	19	31.5	30.9	.23	10.2	.64
4BC-10+	95	2.8	2.4	675	1,425	.047	915	1,905	.048	435	880	580	5	15	30.3	30.3	.23	10.1	.64
4BC-12	95	2.8	2.4	910	2,045	.044	925	2,390	.039	415	1,140	690	1	4	30.4	26.9	.24	10.4	.64
5BF-10+	175	4.0	2.6	1,010	1,760	.057	1,750	4,370	.040	690	1,945	470	7	28	26.6	25.8	.12	5.5	.48
5BC-10+	170	2.7	2.1	1,045	1,975	.053	1,675	4,150	.040	730	1,780	405	9	32	23.4	22.9	.12	5.2	.47
6BF-10+	125	4.0	1.7	790	1,420	.055	1,230	3,035	.041	725	1,590	375	9	25	27.0	26.1	.14	6.0	.50
6BC-10+	140	2.9	1.7	940	1,835	.051	1,515	3,825	.040	745	1,945	505	4	18	23.6	22.3	.13	5.7	.49
7BF-7½	185	4.0	2.9	1,515	2,910	.052	1,655	4,000	.041	635	2,370	615	6	17	27.4	28.4	.13	5.9	.54
7BF-10+	185	4.0	3.0	1,500	3,160	.047	1,785	4,125	.043	575	2,080	670	4	15	25.1	26.4	.13	5.8	.55
7BF-12	185	4.0	3.8	1,850	3,840	.048	1,990	4,950	.040	515	2,630	790	3	10	21.1	21.7	.13	5.6	.50
7BC-7½	95	3.1	2.5	750	1,535	.049	900	2,330	.039	775	1,060	370	7	28	30.3	30.1	.13	5.6	.54
7BC-10	95	3.1	2.5	770	1,645	.047	925	2,795	.033	570	1,010	385	7	30	28.0	25.1	.14	6.3	.54
7BC-12	95	3.1	3.4	750	1,675	.045	925	2,550	.036	610	1,375	450	5	19	24.3	23.5	.13	5.9	.51

8BF-7½	125	3.9	1.6	1,645	2,380	.069	1,745	2,970	.059	500	2,000	930	5	13	30.7	30.3	.20	8.9	.61
8BF-10+	125	3.9	2.0	1,560	2,535	.062	1,755	3,240	.054	440	2,190	1,090	4	7	29.4	27.8	.22	9.9	.62
8BF-12	125	3.9	2.7	1,795	3,195	.056	1,930	3,840	.050	425	2,010	1,370	3	7	27.2	27.5	.24	10.8	.65
8BC-10	85	2.4	2.7	1,025	1,920	.053	1,100	2,185	.050	480	1,360	710	3	9	31.4	31.0	.20	8.9	.61
9BF-7½	170	4.6	2.1	1,605	2,850	.056	1,595	3,470	.046	510	2,150	600	5	14	29.6	30.5	.16	7.0	.57
9BF-10+	170	4.6	2.6	1,720	3,440	.050	1,630	3,955	.041	485	2,580	805	4	12	27.4	25.8	.15	6.8	.55
9BF-12	170	4.6	2.8	1,930	3,655	.053	1,935	4,325	.045	475	2,350	880	3	11	25.3	23.7	.16	7.0	.56
9BC-10	105	2.5	2.5	910	2,065	.044	1,050	2,575	.041	500	1,265	455	7	19	28.2	29.0	.16	7.2	.56
10BF-10+	140	3.7	2.8	1,010	1,505	.067	1,215	2,260	.054	480	2,140	735	4	13	32.4	30.2	.19	8.3	.58
10BC-9½	105	3.3	2.6	795	1,470	.053	820	1,960	.042	475	1,450	610	5	15	33.8	29.2	.21	9.0	.60
11BF-11	140	4.9	3.4	1,190	1,935	.061	1,385	2,620	.053	530	2,230	840	2	8	34.7	31.6	.18	8.1	.58
11BC-9½	100	2.6	2.5	720	1,165	.062	865	1,785	.048	525	1,115	540	5	14	34.6	30.5	.20	8.7	.59
12BF-9½	145	4.2	2.4	1,090	1,580	.069	1,355	2,275	.059	400	2,120	620	7	16	32.0	29.2	.20	8.7	.58
12BC-9½	125	3.0	2.6	875	1,470	.059	1,095	2,370	.046	410	1,420	750	4	11	31.8	27.3	.21	9.2	.59
13BF-8+	255	3.1	2.3	1,665	2,515	.066	1,855	3,080	.060	400	2,380	730	9	21	24.8	25.3	.22	9.7	.63
13BF-9½	255	3.1	2.2	1,825	2,875	.063	1,795	3,610	.050	420	2,570	920	3	7	23.7	25.3	.23	10.2	.63
13BF-12	255	3.1	3.0	2,005	3,120	.064	1,785	3,800	.047	350	2,870	970	3	6	22.6	23.0	.25	11.0	.66
13BC-7½	115	2.6	1.8	890	1,390	.064	965	2,025	.048	515	1,250	460	6	23	28.2	27.9	.22	9.9	.62
13BC-9½	115	2.6	2.7	790	1,470	.053	970	2,130	.045	535	1,110	510	5	20	27.1	27.1	.23	10.1	.61
13BC-12	115	2.6	1.8	955	1,725	.055	1,000	2,290	.044	475	1,480	630	5	16	26.0	26.2	.24	10.6	.63
14BF-8+	135	4.9	.6	890	1,055	.084	1,320	2,305	.057	665	1,530	560	5	16	34.0	33.4	.13	5.8	.52
14BF-10	135	4.9	1.7	1,000	1,320	.075	1,340	2,410	.056	775	1,465	675	2	9	32.4	34.0	.15	6.4	.51
14BF-12	135	4.9	2.4	1,100	1,610	.068	1,250	2,950	.042	625	1,805	760	3	9	31.1	31.7	.17	7.4	.57
14BC-7½	75	2.8	1.8	380	505	.075	750	795	.094	890	930	310	10	41	36.2	36.0	.15	6.7	.53
14BC-10	75	2.8	2.8	485	665	.073	785	1,030	.076	885	985	395	7	26	34.7	34.7	.15	6.8	.53
14BC-12	75	2.8	3.0	495	770	.064	760	1,545	.049	810	1,155	420	3	17	33.3	33.8	.17	7.6	.56
15BF-9½	150	4.4	2.9	1,725	2,790	.061	1,790	3,160	.057	460	2,240	1,000	4	9	29.1	29.5	.18	8.1	.58
15BC-11	95	2.9	3.0	710	1,575	.045	1,005	2,060	.049	550	890	475	6	19	26.9	28.3	.17	7.6	.57
16BF-10½	140	4.6	2.4	1,640	3,345	.048	1,725	3,840	.045	415	1,710	825	5	14	25.4	27.5	.19	8.4	.56
16BC-9½	210	4.1	4.3	1,765	3,605	.049	1,560	3,640	.043	435	1,990	910	5	14	23.8	24.9	.18	8.0	.56
17BF-9½	140	3.9	3.1	1,405	2,050	.068	1,560	2,360	.066	550	2,050	825	2	7	32.8	32.9	.18	7.8	.57
17BC-10½	100	2.5	2.7	730	1,205	.060	800	1,975	.040	625	990	565	5	15	31.5	31.2	.18	7.8	.57
18BC-11	105	3.5	2.8	1,085	2,235	.048	1,160	2,790	.041	425	1,170	790	5	11	25.1	26.2	.20	8.7	.60
19BC-11	95	3.6	3.1	1,095	2,585	042	1,215	3,520	.034	445	880	760	4	12	23.7	23.8	.16	7.2	.54
20BC-10½	90	3.9	4.1	1,025	2,005	.051	1,145	2,695	.042	440	1,050	650	4	10	26.8	26.7	.19	8.3	.56
K-7½	100	2.3	1.2	595	930	.064	860	1,910	.045	730	790	430	9	33	31.5	30.1	.15	6.7	.57
K-10	100	2.3	2.1	580	1,290	.045	945	2,445	.039	805	935	525	4	15	29.2	29.2	.16	6.9	.55
K-12	100	2.3	2.9	710	1,440	.049	980	2,340	.042	740	1,025	610	2	11	26.8	27.2	.16	7.1	.54
L-7½	85	2.6	1.9	495	815	.060	710	1,165	.061	460	630	380	5	20	32.2	31.6	.17	7.5	.57

[1] Computed outer fiber strain or elongation $= \frac{\text{modulus of rupture}}{\text{modulus of elasticity}}$.

[2] The values given represent the average temperature resulting after testing 3 to 5 saggers.

TABLE 2.—*Properties of sagger bodies*—Continued

Body No. and cone at which fired	Modulus of rupture of unfired body	Dry shrinkage	Fired shrinkage	Tested at 20° C.			Tested at temperature at which sagger failed in quenching test				Tested at 1,000° C.		Total plastic deflection in inches (taken from plastic flow curves). Stress of approximately—		Porosity of bars	Porosity of saggers	Total expansion from atmospheric temperature to 250° C.	Coefficient of expansion atmospheric temperature to 250° C.	Total expansion from atmospheric temperature to 1,000° C.
				Modulus of—		Computed[1] outer fiber strain	Modulus of—		Computed[1] outer fiber strain	Sagger[2] failing at	Modulus of—								
				Rupture	Elasticity		Rupture	Elasticity			Rupture	Elasticity	120 lbs./in.²	240 lbs./in.²					
	Lbs./in.²	*Per cent*	*Per cent*	*Lbs./in.²*	*1,000 lbs./in.²*	*Per cent*	*Lbs./in.²*	*1,000 lbs./in.²*	*Per cent*	*°C.*	*Lbs./in.²*	*1,000 lbs./in.²*	*$\times 10^{-4}$*	*$\times 10^{-4}$*	*Per cent*	*Per cent*	*Per cent*	*$\times 10^{-6}$*	*Per cent*
L-10	85	2.6	2.5	705	1,300	0.054	815	1,790	0.046	465	900	750	3	10	30.0	30.9	0.23	10.2	0.61
L-12+	85	2.6	2.4	755	1,500	.050	935	1,915	.049	435	1,090	960	2	9	27.4	28.5	.25	10.9	.63
M-7½	95	2.5	1.7	550	920	.060	710	2,035	.035	475	545	220	5	19	29.3	29.8	.21	9.3	.61
M-10	95	2.5	2.4	715	1,265	.056	855	2,160	.039	490	865	765	3	11	29.0	28.7	.21	9.5	.63
M-12+	95	2.5	3.5	755	1,620	.046	965	2,205	.044	415	905	840	5	12	26.0	26.7	.24	10.5	.67
A-9½	110	4.6	4.3	1,235	2,440	.050	1,185	3,150	.038	410	1,795	1,400	1	4	28.5	27.5	.18	7.9	.57
B-9½	85	4.6	4.4	1,095	2,325	.047	1,450	3,150	.046	435	1,615	1,195	1	4	30.5	29.7	.20	9.0	.61
C-10	90	3.2	2.8	915	1,775	.051	760	2,325	.033	635	1,155	520	2	11	26.5	25.6	.14	6.3	.51
E-10	95	3.9	2.9	825	1,240	.066	1,155	2,080	.055	485	1,490	755	5	11	32.9	31.7	.18	7.8	.57
F-9½	55	3.8	3.1	930	1,810	.051	1,200	2,285	.052	410	1,385	910	3	8	31.6	31.9	.21	8.9	.63
G-9½	55	3.4	6.6	880	2,160	.040	885	2,525	.035	435	1,290	855	2	5	30.0	30.1	.21	9.1	.59
H-9½	40	2.7	2.7	665	970	.068	1,090	2,155	.051	710	1,230	520	4	10	27.6	28.3	.17	7.5	.56

[1] Computed outer fiber strain or elongation $= \frac{\text{modulus of rupture}}{\text{modulus of elasticity}}$.

[2] The values given represent the average temperature resulting after testing 3 to 5 saggers.

The results show that the thermal expansions of the bodies change with the temperature of firing, but such changes are not consistently either in the same direction or of the same magnitude. This, naturally, must be expected because of the various types of clays used in compounding the bodies. The thermal expansion data for two typical bodies fired at three different temperatures are given in Figure 1.

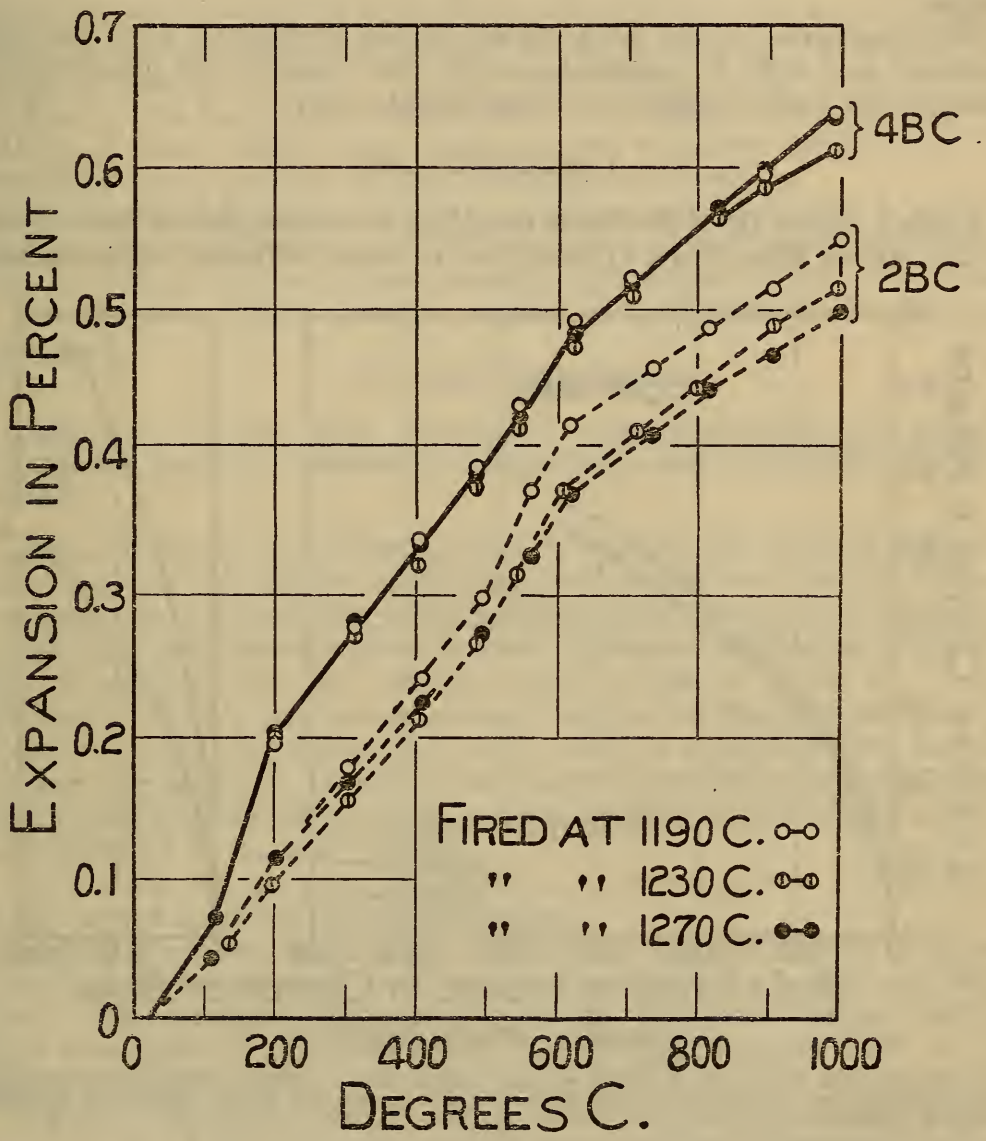


FIGURE 1.—*Showing the linear thermal expansion of two typical sagger bodies fired at three different temperatures*

The great difference in total expansion at 200° C. is well illustrated

Body 4BC shows little change in expansion when tested after firing at each of three temperatures, whereas the expansion of body 2BC decreases with increased temperature of firing. The great difference in the rate of expansion below 200° C. is very noticeable in these two bodies.

Moduli of rupture and elasticity values were obtained at three different temperatures for all bodies (two only for 1BC–8). Check determinations were made of all bodies (one only for 4BC and 20BC) at ordinary temperatures, and of 20 bodies at 1,000° C. In all cases the values obtained for any one body were within approximately 10 per cent of the mean.

The computed maximum outer fiber strain (elongation) is given for all bodies, both at room temperature and at the temperature at which the saggers failed in the thermal shock test. These values show how the elongation of the material decreases in most cases at the higher temperature. The data show that the fine-grogged bodies have a greater fiber elongation before rupture than the coarse-grogged bodies.

The maximum outer fiber strain is not computed with the data obtained at 1,000° C.; instead a study was made of the plastic deflections of the bodies which was more satisfactory.

3. PLASTIC FLOW

Table 2 shows the deflections resulting from the plastic flow of each of the bodies after firing at from one to three different temperatures.

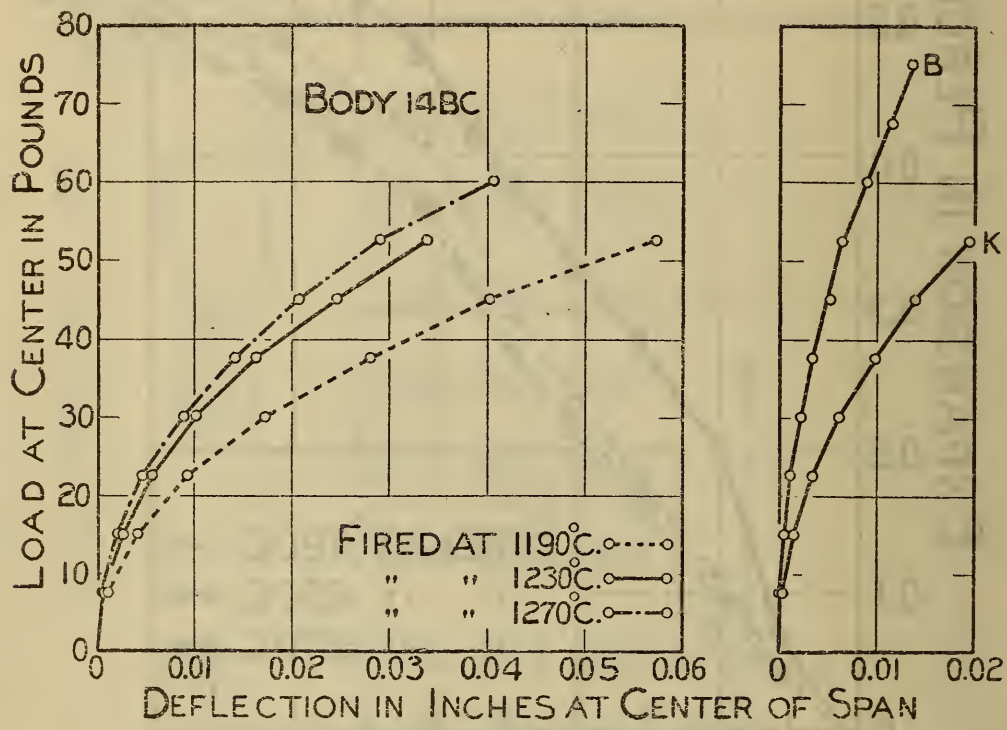


Figure 2.—*Plastic deflections*

Left: Showing that the plastic deflection of sagger bodies tested at 1,000° C. decreases with increase of firing temperature. Right: Plastic deflections at 1,000° C. obtained on two commercial bodies after firing at 1,230° C.

The results were obtained at 1,000° C. and represent the total plastic deflection in inches, at the end of 10 minutes with, first, a load of 120 lbs./in.^{2}, and second a load of 240 lbs./in.^{2}, applied midspan of the 1 by 1 by 12 inch specimens on a 10-inch span. Within the limits of firing temperatures and grog sizes used, the following information relative to plastic flow was obtained:

1. Bodies containing the coarser sizes of grog have a plastic flow decidedly greater than those containing the finer sizes of grog.

2. The plastic flow decreases with increase of temperature of firing of the specimens. A typical illustration of such changes is shown with body 14BC in Figure 2. Saggers fired at the lowest temperature may prove unsatisfactory in service, whereas if fired at the highest temperature may prove to be quite satisfactory. Data represented

by these curves illustrate further the undesirability of heavily loading saggers which have not been fired at sufficiently high temperatures.

3. The percentage increase in plastic flow when loads of 120 and 240 lbs./in.^{2} are used is decidedly different for the different clays.

4. The percentage flux content is an important factor in the tendency of the bodies to flow at high temperatures. Bodies containing a high percentage of silica and a high percentage of flux have a greater plastic flow than bodies containing less silica and more alumina with a high percentage of flux. On the other hand, bodies high in silica and low in flux have a low plastic flow. The silica, alumina, and flux content of these bodies were based on the chemical analyses of the individual clays reported in the first progress report.[4]

The plastic deflections obtained on commercial bodies B and K, after having been fired at cone 10, are shown in the right-hand graph. (Fig. 2.) Body K has a considerably higher plastic flow than body B, but K has a much greater resistance to failure in the thermal-shock tests.

VI. DISCUSSION

1. AVERAGE VALUES FOR POROSITY, TEMPERATURE AT WHICH SAGGERS FAILED, THERMAL EXPANSION, AND PLASTIC DEFLECTIONS

A comparison of the average porosity values and average temperatures at which the saggers cracked in the thermal-shock test indicated, in general, that the saggers which had a porosity intermediate between the highest and lowest values showed the least resistance to failure. This is indicated by the average values given in Table 3. H. G. Schurecht found a somewhat similar relation in connection with his study of the spalling losses of fire-clay brick in malleable-iron furnace linings.[5] In order to illustrate the point more fully, saggers which had a porosity below 20 per cent, as reported in the preceding report,[6] were included in these averages.

The values for porosity in Table 3 represent group relationships which do not hold for individual bodies.

Table 3 also gives the average porosity and temperatures of failure when the coarse-grogged and fine-grogged bodies are grouped separately. The average temperature at which the coarse-grogged saggers failed was 605° C. and that of the fine-grogged saggers 535° C., an appreciable difference.

The total expansions from atmospheric temperature to 250° C. are also averaged and correspond with the grouping of porosity values. The maximum expansion occurred with bodies which had a porosity of 28 per cent, and in turn fail in the thermal shock test at the lowest average temperature. A comparison of the average thermal expansion values with the average temperatures at which the saggers failed shows that a very close relation exists between these two properties.

The total plastic deflections determined at 1,000° C. with a stress of approximately 240 lbs./in.^{2} are included with the averages of other properties in Table 3. There appears to be a general relation of plastic deflection to the other properties. The average values for plastic deflection when the coarse and fine grogged bodies are sepa-

[4] See footnote 1, p. 1017.
[5] The Behavior of Fire Brick in Malleable Iron Furnaces. Trans. Am. Foundrymen's Association, Vol. 30, p. 391–94.
[6] See footnote 1, p. 1017.

rated show clearly that the coarse-grogged bodies have decidedly greater plastic flow than the fine.

TABLE 3.—*Average values of porosity, nature of grog, temperature of failure, and plastic flow of all laboratory-made sagger bodies*

Total number of bodies	Porosity [1]	Temperature at which saggers failed in thermal-shock test	Thermal expansion total at 250° C.	Total plastic deflection at 1,000° C. with a stress of approximately 240 lbs./in.²
	Per cent	*°C.*	*Per cent*	*Inches per 10-inch span*
16	19.0 (16–21.9)	600	0.110	0.00525
12	24.0 (22–25.9)	530	.170	.00175
10	26.0 (26–26.9)	500	.190	.00200
13	28.0 (27.0–29.9)	475	.200	.00150
7	30.0 (30.0–30.9)	525	.190	.00175
9	32.0 (31.0–32.9)	630	.160	.00175
7	35.0 (33.0–38.0)	800	.150	.00275
COARSE-GROGGED BODIES ALONE				
	26.7	605	0.171	0.00240
FINE-GROGGED BODIES ALONE				
	26.3	535	0.171	0.00143

[1] The average porosity in each case included those bodies coming within the range of porosity values given in the parentheses.

2. CORRELATION OF THERMAL EXPANSION, COMPUTED MAXIMUM OUTER FIBER STRAIN AND TEMPERATURE AT WHICH SAGGERS FAILED

In correlating the properties of the sagger bodies which were determined, it was necessary to separate the data obtained on the coarse and fine-grogged bodies because of such properties as thermal conductivity and diffusivity which were not studied and which undoubtedly are not the same in the two types of bodies. Because of the fact that several of the bodies studied were identical except for the sizes of the grog they contained and, because the coarse-grogged bodies showed the greater resistance to failure in the thermal shock test in spite of having the lower computed fiber elongation it must be assumed that the thermal conductivity and other thermal properties have an important effect on the life of the sagger.

Figures 3 (fine-grogged bodies) and 4 (coarse-grogged bodies) show the relation that thermal expansion (abscissa) and computed maximum fiber elongation (ordinate) bear to the resistance of the saggers to failure when subjected to thermal shock (vertical line). These models were made because they illustrate very clearly the importance of controlling, first the thermal expansion and, second the maximum fiber elongation if it is desired to obtain a high resistance of saggers to failure when subjected to temperature changes. Figure 3 (A), and Figure 4 (A), were taken to show the scattering of the points in the horizontal plane; Figure 3 (B), taken along the abscissa shows the increasing resistance of saggers to failure with decreasing thermal

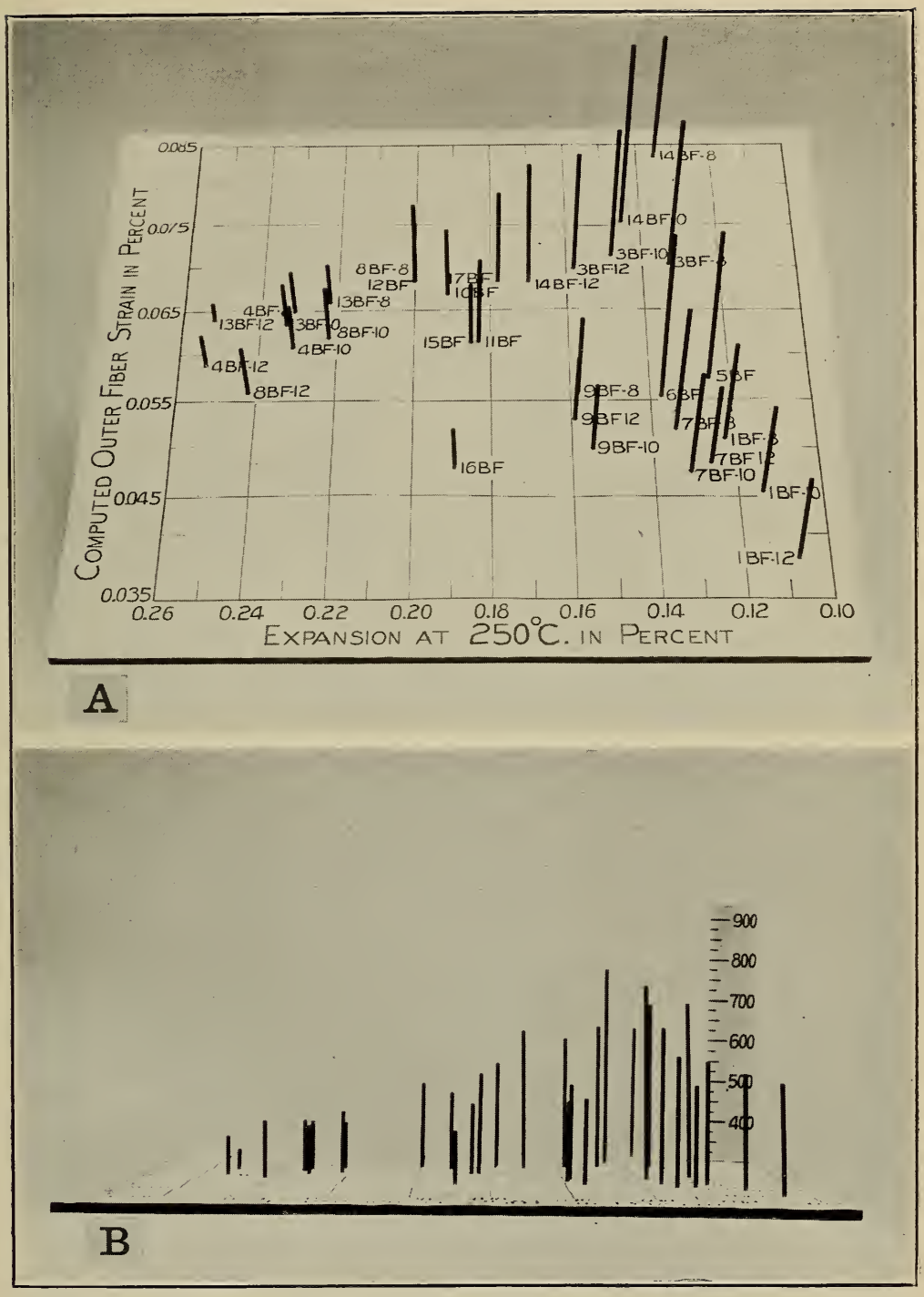


FIGURE 3.—*Three dimensional models illustrating the properties of fine-grogged sagger bodies*

A, The relation between linear thermal expansion (abscissa), computed fiber elongation (ordinate) and the resistance of saggers to failure due to thermal shock (vertical); *B*, the gradual decrease in resistance to failure due to thermal shock (indicated by the height of the pegs) is accompanied with increase of total expansion. (Read from left to right.)

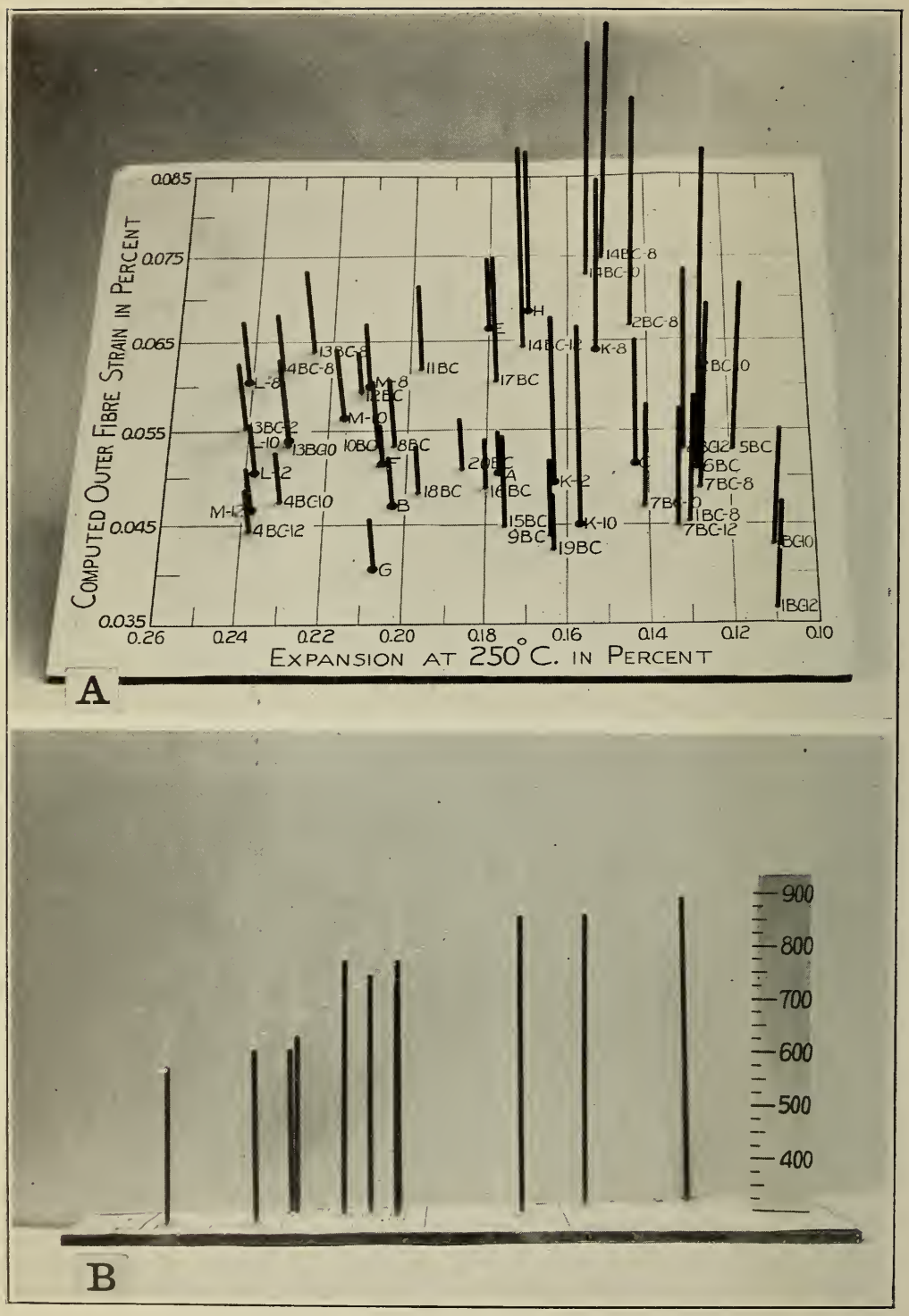


Figure 4.—*Three dimensional models illustrating the properties of coarse-grogged sagger bodies*

A, Similar to Figure 3(*A*); *B*, the increase in resistance to failure due to thermal shock is accompanied by increased computed fiber elongation. (Read from left to right.)

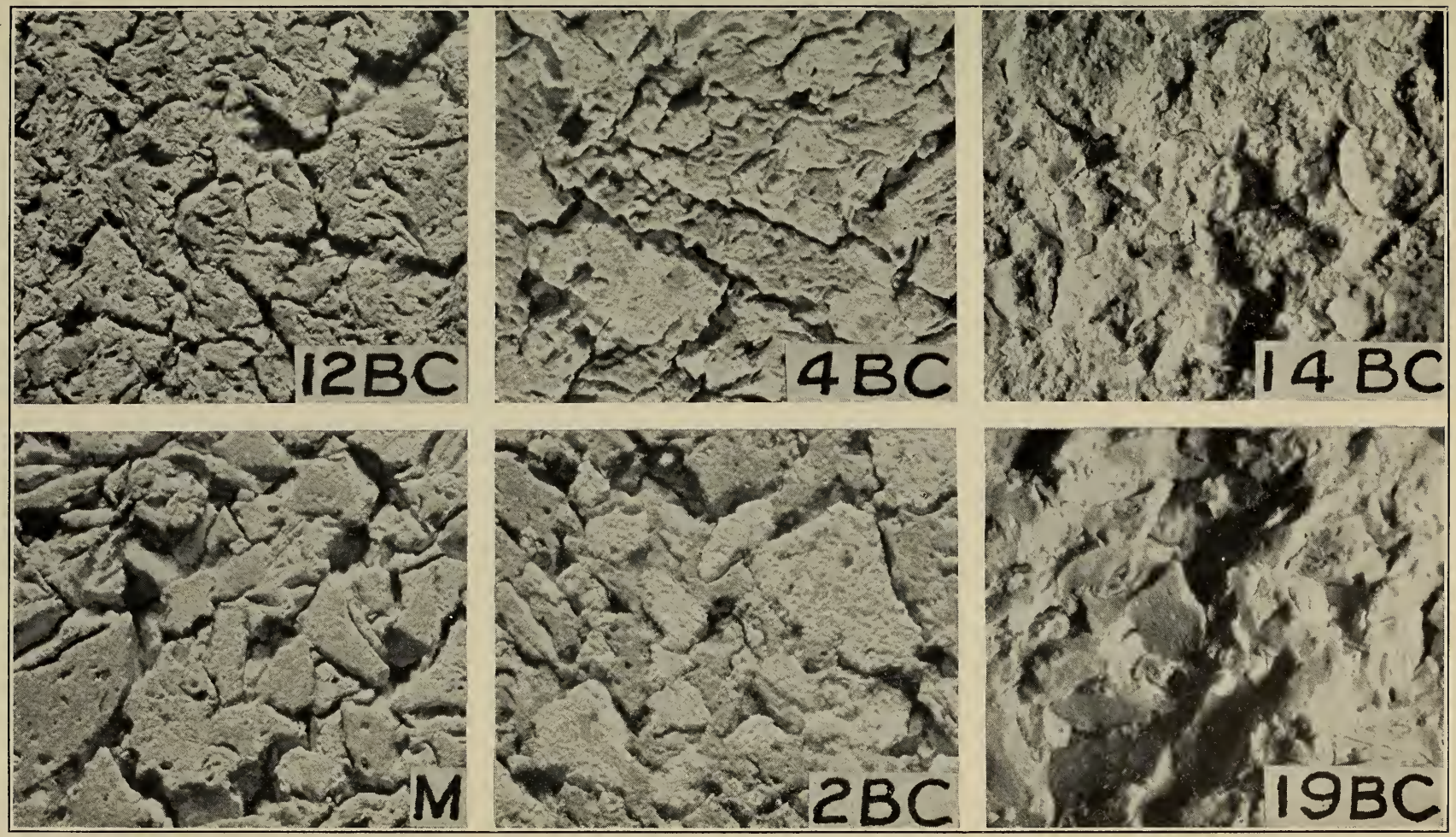


FIGURE 5.—*Photomicrograph (6 diameters) showing structure of six different sagger bodies*

expansion and Figure 4 (B), taken along the ordinate axis, indicates that if the thermal expansion is maintained within the range of 0.10 to 0.15 per cent, the bodies show greater resistance to failure, indicated by the height of the pegs, as the computed maximum fiber elongation becomes greater. The models also show that it is most important to keep the total expansion from 20° to 250° C. below 0.18 per cent, or the coefficient for this temperature range below 8×10^{-6}. The necessity for this is especially obvious from an examination of Figure 4, which shows a sharp line of demarcation from saggers having good resistance to failure to those having poor resistance at approximately the position of the line indicating a total expansion of 0.18 per cent. The models also show that the resistance of saggers to thermal shock depends more on the thermal dilatation than on the computed outer fiber strain. Furthermore, it is apparently out of the question to develop a sagger of high resistance to failure by increasing the fiber elongation as a result of change in structure of the body if the total thermal expansion from 20° to 250° C. is approximately 0.18 per cent or above.

The trend of the points is more regular in the case of the fine-grogged bodies (fig. 3) than those containing the coarse grog (fig. 4). This is partially due to the fact that the commercial bodies (pegs with circle around the base) are included with the coarse-grogged laboratory prepared bodies. The grog sizing in most of the commercial bodies is more or less haphazard. This would naturally cause some irregularity in the trend of the points. Another cause for irregularity is probably due to the fact that the percentage change in the maximum fiber elongation with increase of temperature is not the same for all bodies. Commercial body "A," Table 2, is an example of the type of body in which the fiber elongation decreases rather rapidly with increase of temperature. Consequently the saggers prepared from this body would fail at a somewhat lower temperature than might be indicated by the computed maximum fiber elongation based on results determined at room temperature and the thermal expansion data.

It is also pointed out that in spite of the care exercised in firing the ware, the temperature within the kiln was sufficiently nonuniform to account for differences in the physical properties between bar specimens and saggers though both were prepared from the same body and fired at the same time. This condition is well illustrated if the porosities of the bars and saggers are compared. Although in most instances the differences are small, attention is directed to the fact that the differences in other properties may be quite pronounced. For example the data show that a change of 10 per cent in the value for porosity due to firing at the higher temperatures might easily account for a 50 per cent change in modulus of elasticity. (Bodies 3BF, 14BF, Table 2.) In correlating the results obtained on bar specimens with those obtained on the saggers, some of the apparent discrepancies can easily be accounted for by the slight differences in firing treatment which the ware received.

3. BODY STRUCTURE

Figure 5 shows the structure of various types of sagger bodies. Body 12BC and commercial body "M" are of greatly different structure, but have very nearly the same linear thermal expansion and

maximum fiber elongation. The reasons for the poor resistance to failure shown by saggers prepared from these bodies is probably due to their comparatively high thermal expansion below 250° C. and the rapid decrease in maximum fiber elongation with increase of temperature. The grog particles in body "M" are not well bonded, but because of the angular shape of the grog which permits interlocking of the particles, a high fiber elongation is obtained. Bodies 2BC and 4BC have the same computed maximum fiber elongation, but have greatly different thermal expansion. The porosity of the grog in body 2BC is greater than that in 4BC. As a result the resistance to failure shown by body 2BC is almost twice as great as that shown by 4BC. Bodies 14BC and 19BC have a relatively low and very nearly the same thermal expansion, but the maximum fiber elongation determined at 20° C. was very much greater for 14BC than 19BC. As a result of both the favorable fiber elongation and thermal expansivity saggers prepared from body 14BC did not crack in the heat-shock test before reaching 890° C., whereas those prepared from body 19BC cracked at an average temperature of 445° C. A study of the photograph for 19BC shows that the grog used is nearly vitrified. Its effect on the structure was undoubtedly one of the primary causes of the comparatively low resistance to failure of saggers prepared from body 19BC.

Some information on the effect of resistance of saggers to failure when subjected to heat shock and when using open and dense firing clays as grog in the body compositions was given in the preceding report.[7] Additional data have been obtained, and are summarized in Table 4, to show the advantage of using open burning grog rather than the dense burning. The table is made up of five groups, the bond remains unchanged in each of the bodies of any one group, but the grog is varied. A comparison is intended between the members of a group and not between the groups.

TABLE 4.—*Temperatures of failure of saggers and porosities of clay and grog in the bodies*

Group	Body No.[a]	Average porosity of clays	Average porosity of grog	Temperature at which saggers cracked
		Per cent	*Per cent*	*° C.*
A	1BC	28.0	14.0	635
	2BC	28.0	32.0	865
B	10BF	33.0	33.0	480
	11BF	33.0	36.0	530
	12BF	33.0	30.0	400
C	10BC	33.0	33.0	475
	11BC	33.0	36.0	525
	12BC	33.0	30.0	410
D	15BF	31.0	31.0	460
	16BF	31.0	26.0	415
	17BF	31.0	36.0	550
E	15BC	31.0	31.0	550
	16BC	31.0	26.0	435
	17BC	31.0	36.0	625

[a] See Table 1 for body compositions.

[7] See footnote 1, p. 1017.

These results, as well as those previously reported, show that in every case the sagger life is increased as grog of greater porosity is used. Although the fiber elongation is favorably affected with increase of porosity in most cases there are changes in the other properties, such as thermal expansion, which materially affect their life as well.

In conclusion, it might be stated that the results of the entire study indicate that in the majority of instances it is desirable to analyze the conditions of service under which saggers are to be used. In most cases it is apparently impossible to prepare sagger bodies from the usual run of sagger clays without sacrificing one or more desirable properties for the sake of some one property which the user deems to be paramount to all others. For instance, if it is considered necessary or desirable to have a strong sagger with a low plastic deflection, it would be advisable to eliminate the coarser sizes of grog. The resistance to failure due to thermal shock would necessarily have to be sacrificed to some extent. On the other hand, where resistance to thermal failure is of primary importance and where the load is light, so that plastic deflection is of minor consideration, a coarse grogged body with a low thermal expansion should be chosen. In other words, by knowing the properties of the material entering into a body, it is possible to make saggers having properties which are considered the most desirable for the service intended and which approach the best that may be obtained with such clays.

VII. SUMMARY

From 5 to 12 small saggers were made from each of 35 laboratory prepared sagger bodies and from each of 10 commercially prepared bodies. The 35 bodies were prepared from combinations of 28 different clays, some of which were used only as the bond, others as both grog, obtained after firing, and bond. The majority of the bodies were made in two series, one of which was prepared with coarse grog and the other with fine grog. The saggers were tested for resistance to heat shock after firing at one or all three of the following temperatures, namely, 1,190°, 1,230° and 1,270° C. Specimen bars were made to correspond with each set of saggers and fired simultaneously with the saggers. These bars were used for determining linear thermal expansion from 20° to 1,000° C., porosity, moduli of elasticity and rupture and plastic flow at 1,000° C.

The data show that increases in the temperature of firing, although evidenced by comparatively small decreases in the porosity of the sagger bodies may cause great increases in the modulus of elasticity. This in turn affects the maximum fiber elongation unfavorably and thereby decreases the resistance of saggers to failure due to thermal shock.

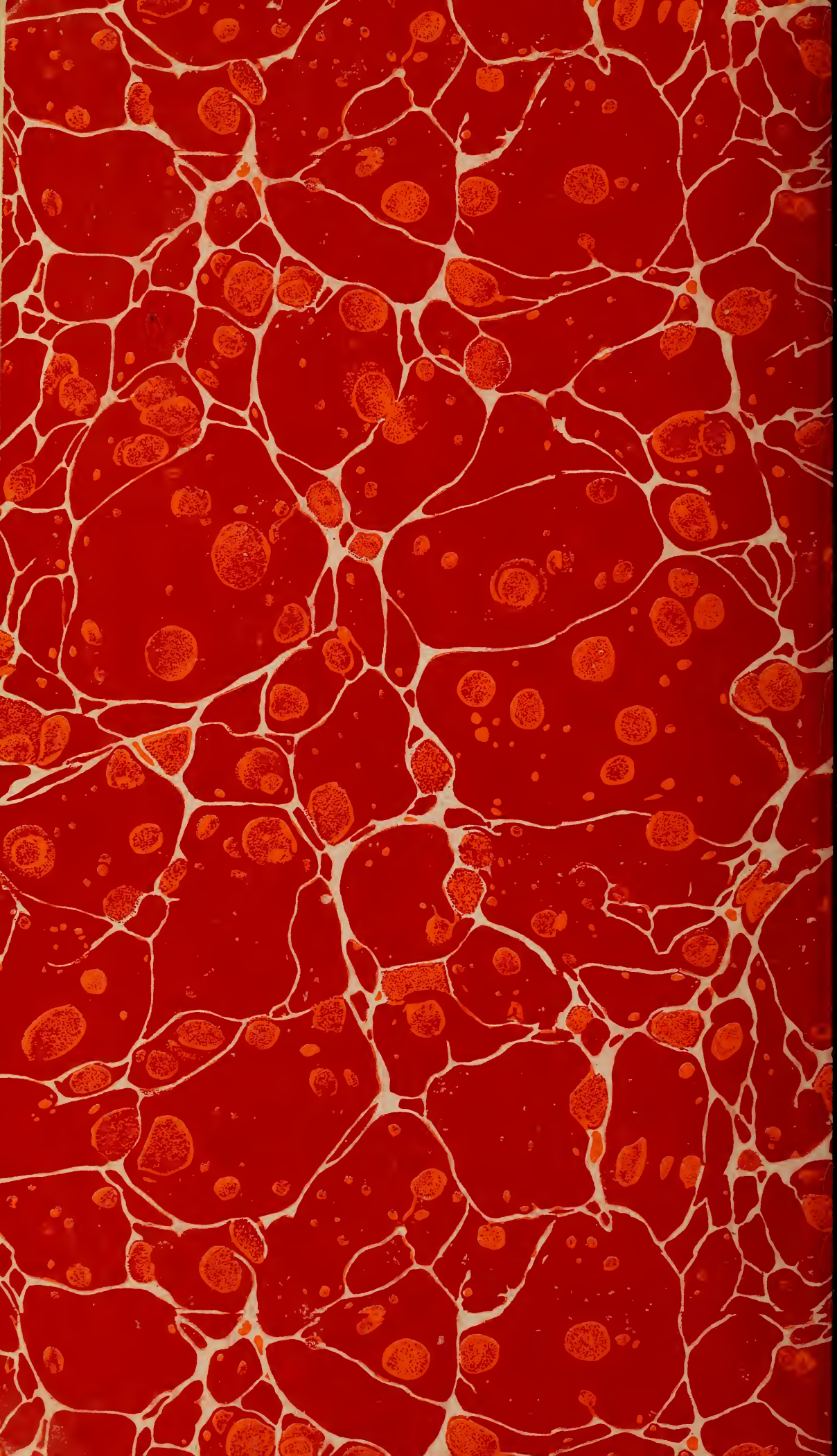
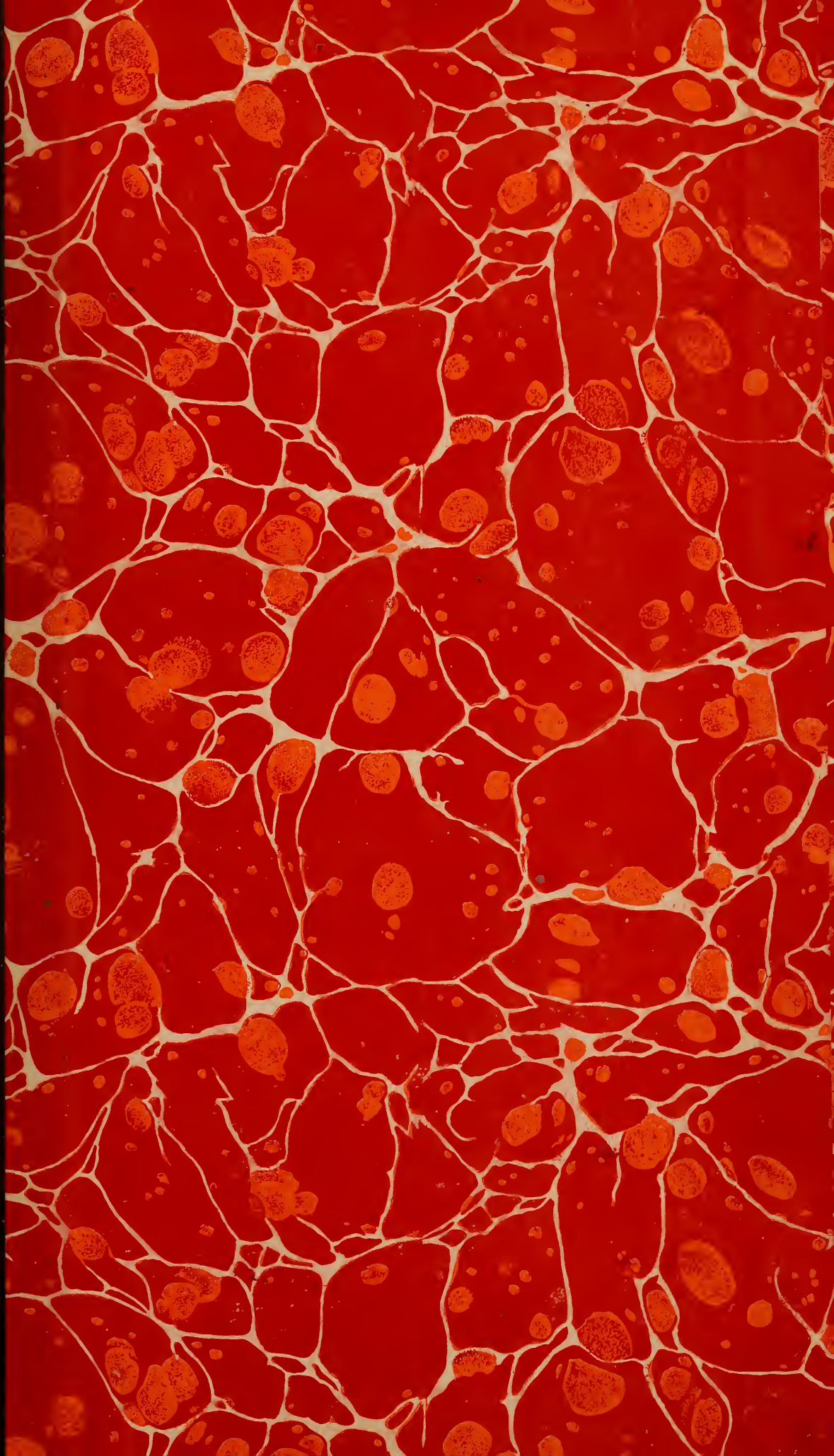
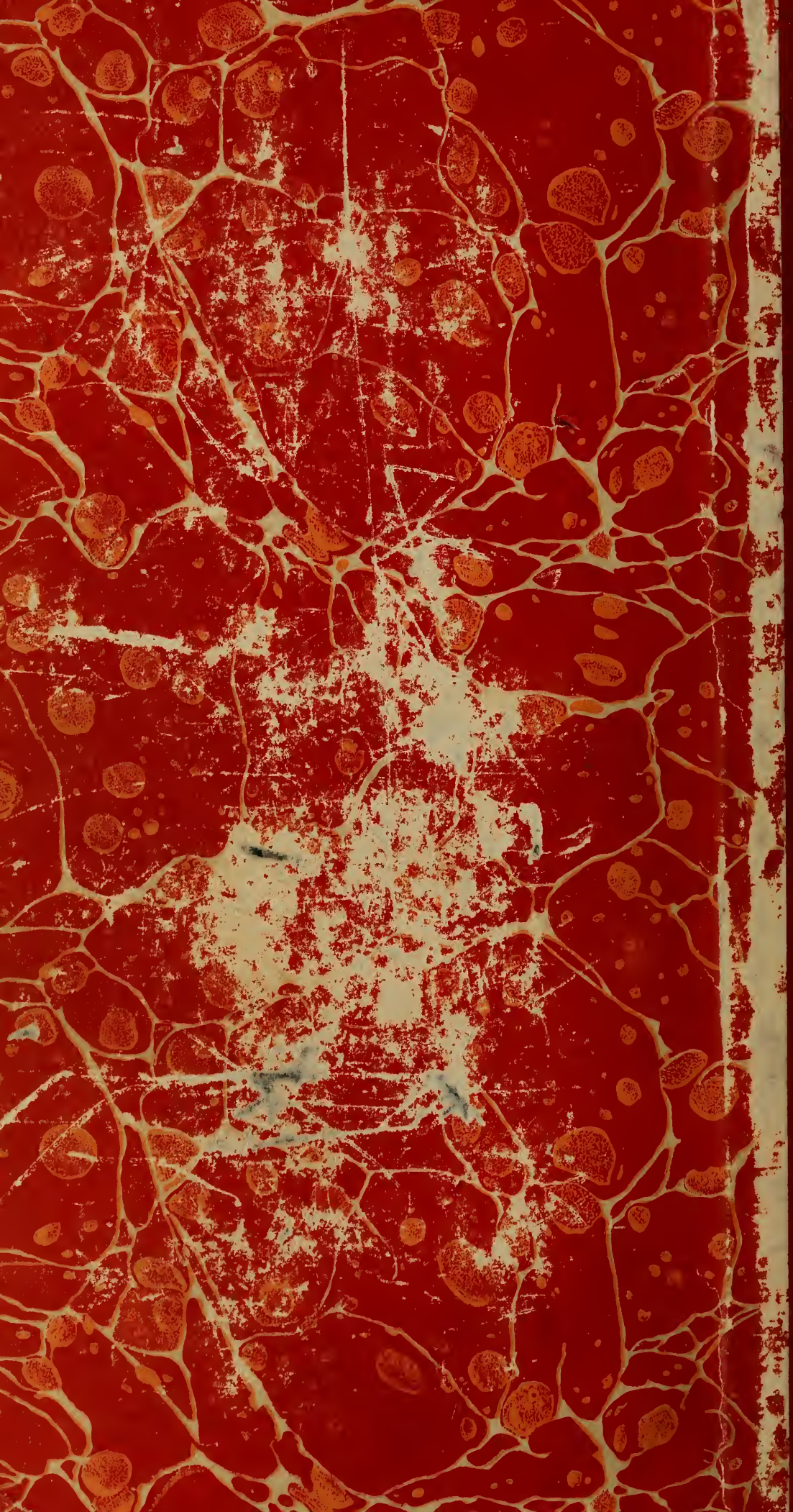
The linear thermal expansion of the bodies changes with increase of temperature of firing, but such changes are not consistently either in the same direction or of the same magnitude.

Data are given to show the importance of controlling, first, the linear thermal expansion and, second the maximum fiber elongation if it is desired to obtain a high resistance of saggers to failure due to thermal shock. A total linear thermal expansion from 20° to 250° C. of approximately 0.18 per cent or greater practically precludes the possibility

of obtaining a sagger having a high resistance to thermal shock. The life of the sagger is more sensitive to changes in thermal expansion than to changes in the computed outer fiber elongation.

The plastic flow studies at 1,000° C. show that:

1. Bodies containing the coarse sizes of grog have plastic deflections decidedly greater than those containing the fine grog sizes.
2. The plastic flow decreases with increase of temperature of firing of the specimens.
3. The flux content is an important factor in the tendency of the bodies to flow or deform at high temperatures, and is more serious if the silica content is high.

The results show that it is very desirable to analyze the conditions of service under which saggers are to be used because in most cases it is impossible to prepare sagger bodies, from the usual run of clays, which have properties ideally suited for longevity in all types of service. By studying the properties of the finished sagger body and the clays and grog constituting it, it is possible to make quality saggers limited only by the character of the materials used.

WASHINGTON, May 29, 1931.