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A STUDY OF SAGGER CLAYS AND SAGGER BODIES

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ABSTRACT

Fifty-one clays of the type used for saggers were studied with respect to chemical composition and also with respect to various physical properties both before and after heating at different temperatures. The tests indicated that certain clays had similar properties; consequently the later phases of the investigation were limited to 36 clays. Eighty-five sagger bodies were prepared from these clays by blending equal weights of each of 2 clays and either a fine-graded grog or a coarse-graded grog. Various physical properties of the bodies were determined after heating them at one of each of several temperatures within the range in which saggers are used commercially so that 139 groups of laboratory-prepared specimens of different properties were obtained. Twelve commercially prepared bodies were also studied. The results obtained should enable the manufacturer to (1) produce saggers suitable for particular services, and (2) predict the probable life with respect to resistance to thermal shock, if certain properties of the constituent clays are known.

CONTENTS

I. INTRODUCTION

The practice of maturing both glazed and unglazed pottery in clay containers, or saggers as they are commonly termed, was started hundreds of years ago because of the necessity of protecting the ware from furnace gases, ashes, and rapid changes in temperature and also to make possible the stacking of the ware to heights not otherwise attainable. Saggers have received much discussion in ceramic literature because they are an important item in manufacturing costs of

various ceramic products. Not only do they break and bulge but ware is spoiled when they fail in the kiln. To assist the industry in overcoming difficulties in the use of saggers, the National Bureau of Standards undertook an extended study of a large number of clays used in sagger making and of sagger bodies prepared from those clays. Reports [1] giving in detail the results obtained have been published periodically as specific phases were completed. This paper summarizes the important conclusions reached during the course of the entire study.

Since the inception of this problem much interest has been manifested in the use of talc in sagger mixes. As a result of that interest a few tests were made to determine how the talc affected certain physical properties of the heated sagger body. The information obtained is presented as part of this report although the properties of the individual clays were not determined.

II. MATERIALS AND SCOPE OF STUDY

Among the 51 clays included in the original studies 18 were from New Jersey, 13 from Kentucky, 7 each from Ohio and Tennessee, 2 from California, and 1 each from Georgia, Illinois, Pennsylvania, and South Carolina. The samples were obtained from the consumer whenever possible rather than from the producer in order that experimental results might represent the properties of clays actually furnished to the consumer. These clays were supplemented by a limited number of commercially prepared sagger bodies.

Because of the impracticability of including all clays in every step of the investigation preliminary tests to determine such properties as pyrometric cone equivalents (softening points), strength, porosity, and linear thermal expansion, and the chemical analysis of all the clays were made in order to classify them into a limited number of groups. Representative clays from each group were chosen for further intensive study. Certain properties of these representative clays, the properties of a large number of mixtures of these clays, and the effect on certain properties such as thermal expansion, extensibility, and resistance to thermal shock, when the mixtures are heated at different temperatures, were studied.

III. PREPARATION OF SPECIMENS

Two types of bodies were used, simple and blended. The simple bodies consisted of equal parts by weight of a single clay and grog made from the same clay. The blended bodies were made in most cases from a combination of 2 clays mixed with grog made from the individual clays in each combination. All grog used with the simple bodies was heated at 1,200° C for 1½ hours before being crushed and screened. Thirty percent of this grog passed a no. 20 and was retained on a no. 40 sieve, the remaining 70 percent passed a no. 40

[1] Progress report on investigation of sagger clays. J. Am. Ceram. Soc. **9,** 131 (1926). II. Progress report on investigation of sagger clays—some observations as to the significance of their thermal expansion. J. Am. Ceram. Soc. **9,** 554 (1926). III. Progress report on investigation of sagger clays—their elasticity and transverse strength at several temperatures. J. Am. Ceram. Soc. **10,** 524 (1927). IV. Progress report on investigation of sagger clays—elasticity, transverse strength, and plastic flow at 1,000° C. J. Am. Ceram. Soc. **10,** 995 (1927). Preparation of experimental sagger bodies according to fundamental properties. BS J. Research **3,** 419 (1929) RP104; also J. Am. Ceram. Soc. **12,** 457 (1929). The life of the sagger as affected by varying certain properties. BS J. Research **7,** 1017 (1931) RP387; also J. Am. Ceram. Soc. **14,** 867 (1931). Sagger quality predicted from properties of clays used. J. Am. Ceram. Soc. **16,** 601 (1933).

sieve and included the fines. The grog for the first blended bodies investigated was prepared from clay heated at 1,230° C, but later groups of bodies contained in many cases grog prepared from the broken test specimens used in the first group. The majority of the bodies were prepared in two series similar in every respect except for the size of the graded grog, which was either coarse or fine. The two combinations of grog sizes, taken from several recommended by Kirkpatrick,[2] were as follows:

Combinations of grog	Percent	Passed through sieve no.—	Retained on sieve no.—
Coarse	20	4	8
	60	8	12
	20	12	20
Fine	66⅔	20	40
	33⅓	40	80

Test specimens, made from both simple and blended bodies, consisted of (1) bars 1 in. square in cross section and either 2, 7, or 12 in. long, and (2) small oval saggers 4 by 4 by 6 by ½ in. Some of the specimens were tested in the air-dried condition and the others had been heated for 1½ hours at one of the following temperatures (±10° C): 1,110, 1,150, 1,180, 1,200, 1,230, 1,270, or 1,300° C.

IV. METHODS OF TESTING

The water of plasticity (based on the plastic weight), the volume and linear shrinkage during drying, the porosity and the modulus of rupture of the test specimens were determined in general according to the methods adopted and later published by the American Ceramic Society.[3] The pyrometric cone equivalents (pce or softening points) were determined according to the ASTM standard method C24–20, which is similar to standard method serial designation C24–31.[4] The linear thermal expansions from room temperature to 1,000° C were measured with the apparatus described by Geller and Heindl.[5]

The relative resistance to thermal shock was determined by air-quenching empty saggers from progressively higher temperatures. The initial furnace temperature was 350° C, the second 400° C, and each succeeding temperature was increased 25° C until fracture occurred. The temperature from which they were quenched when fracture occurred is designated as T. The value of T is used as a measure of the resistance of the saggers to thermal shock.

Young's modulus of elasticity of both clays and bodies was determined with an especially designed apparatus.[6] The 1- by 1- by 12-in. bars of the mixtures of clay and grog were heated at the same time as the experimental saggers made of the same mixtures. They were then tested in flexure at several different temperatures between room temperature and 1,000° C. All elasticity tests were made using a span of 10 in.

The plastic deformation of the clays and bodies [7] was determined at 1,000° C only. The same apparatus and type of specimens were used

[2] Table 11 in Tech. Pap. BS **10,** 38 (1918) T104.
[3] J. Am. Ceram. Soc. **11,** 449 (1928).
[4] Am. Soc. for Testing Materials Book of Standards for 1930, part II, p. 184.
[5] J. Am. Ceram. Soc. **9,** 555 (1926). (See footnote 1.) A photograph of the apparatus faces p. 694, BS J. Research **3** (1929) RP114.
[6] For a description of the apparatus see J. Am. Ceram. Soc. **10,** 526 (1927), and for a photograph of it see BS J. Research **3,** 695 (1929) RP114.
[7] J. Am. Ceram. Soc. **10,** 995 (1927) and **12,** 457 (1929). See footnote 1.

for making these tests as for the modulus of elasticity tests. Measurements of the plastic flow under loads of 60 and 120 lb/in.^{2} were made at 5-minute intervals during 1 hour and similarly under a load of 30 lb/in.^{2} during ½ hour.

The total plastic deformation of the bodies was obtained from load-deflection curves. To distinguish between elastic and plastic properties the elastic recovery of the material was considered as the difference between the deflection caused by any particular load at the end of a 10-minute period and the "set" of the material at the end of a 5-minute period after removal of that load.

V. RESULTS

1. CLAYS

(a) RAW CLAYS

The water of plasticity of the 51 clays ranged from 13.7 to 31.7 percent. Forty-seven clays had satisfactory working properties.

The volume drying shrinkage ranged from 9.1 to 16.9 percent, the linear drying shrinkage from 2.8 to 6.1 percent, the porosity from 24.4 to 50.0 percent, and the modulus of rupture of dried clay bars ranged from 45 to 385 lb/in.^{2}

The pyrometric cone equivalents (pce or softening points) ranged from 14 to above 33. In this range 16 clays had a pce of 31 or above, 19 between cones 28 and 30, inclusive, 12 between cones 20 to 27, inclusive, and 4 had a pce equal to or below cone 19.

The chemical compositions of the 51 clays are given in the first progress report.[8] The silica content of 44 of the clays ranged from 50 to 70 percent, 6 contained less silica and 1 contained more. Five of the clays had an alumina content between 35 and 40 percent, 2 had less than 20 percent; the remainder ranged between 20 and 34.9 percent.

(b) HEATED CLAYS

The minimum and maximum results obtained in all tests for modulus of rupture of clays heated in the range 1,110 to 1,310° C are summarized in table 1. The detailed results (not given in this report) show that 15 clays had reached their highest transverse strength as a result of the 1,270° C heating and that 33 clays showed greater strength after having been heated at 1,310° C, although the porosity and volume shrinkage indicate the latter had been overheated at this temperature.

TABLE 1.—*Range in modulus of rupture, porosity, and volume shrinkage of 51 sagger clays heated at different temperatures*

Temperature at which heated	Modulus of rupture		Porosity		Volume shrinkage	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
°C	lb/in.^{2}	lb/in.^{2}	*Percent*	*Percent*	*Percent*	*Percent*
1,110	405	3,850	18.0	23.5	2.2	14.9
1,150	500	4,340	17.4	46.5	1.9	16.3
1,180	510	4,340	13.9	45.9	2.7	18.2
1,230	640	5,350	8.1	40.8	4.0	24.7
1,270	610	4,850	1.0	38.5	2.1	35.7
1,310	755	4,960	8.8	39.2	2.5	30.2

[8] J. Am. Ceram. Soc. **9**, 131 (1926).

The results of the porosity and volume shrinkage determinations are also summarized in table 1. The greatest change in porosity of any clay when heated to the several temperatures given in the table was from 27.5 to 3.4 percent; the least change was from 33.5 to 31.2 percent. The greatest change in volume shrinkage was from 7.9 to 26.3 percent; the least was from 4.1 to 5.3 percent.

The linear thermal expansions of 49 clays which had been heated at 1,230° C were measured from room temperature to 1,000° C. The most distinguishing characteristic is that 34 of the clays showed a rapid increase in the rate of expansion between approximately 100 and 200° C, due to the inversion of alpha cristobalite to the beta form, while 15 failed to exhibit that phenomenon. There was a great difference (approximately 85 percent at 1,000° C) in the expansion between the clay having the greatest total expansion and the one having the least, as is illustrated in figure 1. Several additional curves for individual clays will be given later in conjunction with thermal-expansion data on sagger bodies representing mixtures of 2 or more clays and grogs.

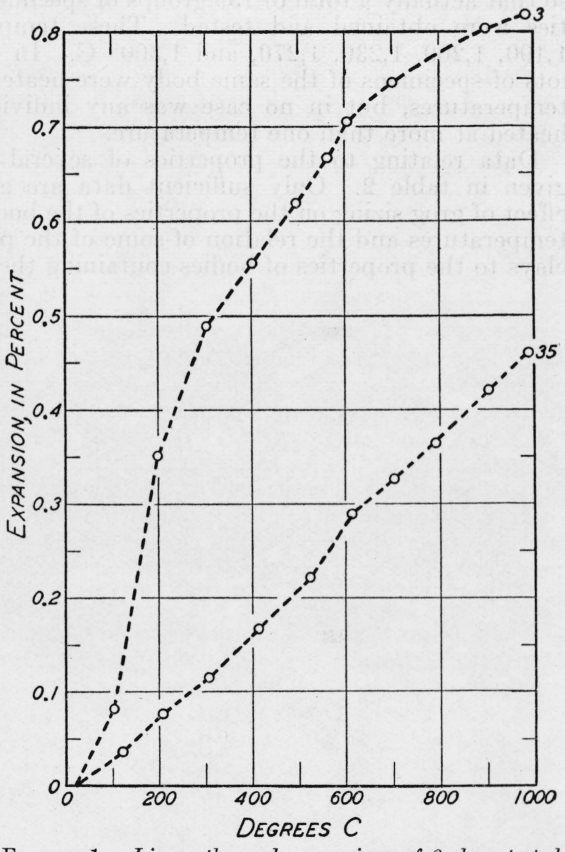

FIGURE 1.—*Linear thermal expansions of 2 clays tested after heating at 1,230°* C.
The expansions represent the extremes obtained.

The moduli of elasticity of 36 clays which had been heated at 1,230° C for 1½ hours were measured at room temperature, at 750° C, and at 1,000° C. The moduli of elasticity of the remaining 15 clays were not determined, because all types of clays included in the investigation were represented by the 36 as far as could be judged from the known properties. The modulus of elasticity at room temperature ranged from 800,000 to 9,430,000 lb/in.^{2} At 750° C the modulus ranged from 1,690,000 to 7,840,000 lb/in.^{2} The modulus at 1,000° C ranged from 300,000 to 1,510,000 lb/in.^{2}

The results of the plastic-flow tests made on 17 clays under the conditions stated, indicate that all the clays which had a pce above

30 showed little difference in the plastic flow, whereas those which had a pce of 30 or below showed not only a greater average plastic flow, but the plastic flow of the several clays in the latter group was approximately inversely proportional to the pce.

2. LABORATORY-PREPARED SAGGER BODIES

Eighty-five bodies were prepared and several of the resulting specimen bars and saggers were heated at any one of several temperatures, so that actually a total of 139 groups of specimens of different properties were obtained and tested. These temperatures were: 1,155, 1,190, 1,200, 1,230, 1,270, and 1,300° C. In some cases 3 different lots of specimens of the same body were heated at one of 3 different temperatures, but in no case was any individual lot of specimens heated at more than one temperature.

Data relating to the properties of several individual bodies are given in table 2. Only sufficient data are given to illustrate the effect of grog sizing on the properties of the bodies heated at different temperatures and the relation of some of the properties of individual clays to the properties of bodies containing these clays.

TABLE 2.—*Properties of some sagger clays and sagger bodies*

Body no. [1]	Approximate temperature of heating	Modulus of rupture R [2]			Modulus of elasticity E [2]			Total linear thermal expansion from 20 to 250° C			Extensibility R/E			Temperature sagger failure	
		Clays [3]	Fine-grogged bodies	Coarse-grogged bodies	Clays [3]	Fine-grogged bodies	Coarse-grogged bodies	Clays [3]	Fine-grogged bodies	Coarse-grogged bodies	Clays [3]	Fine-grogged bodies	Coarse-grogged bodies	Fine-grogged bodies	Coarse-grogged bodies
	°C	lb/in.²	lb/in.²	lb/in.²	1,000 lb/in.²	1,000 lb/in.²	1,000 lb/in.²	Percent	Percent	Percent	Percent	Percent	Percent	°C	°C
1B	1,190		1,720	955		3,370	2,100		0.12	0.13		0.051	0.045	565	635
1B	1,230	{1,800 (21) {1,610 (47)	1,725	995	{3,195 (21) {3,765 (47)	3,800	2,305	{0.15 (21) {.11 (47)	.11	.11	{0.056 (21) {.043 (47)	.045	.043	540	610
1B	1,270		2,095	1,130		5,380	3,095		.11	.11		.039	.036	525	585
2A	1,230	{2,180 (24) {2,310 (32)	1,905	960	{2,180 (24) {2,310 (32)	3,605	1,525	{.13 (24) {.09 (32)	.12	.15	.079	.053	.063	560	680
2A	1,270		2,180	1,130		4,205	2,340				.041	.052	.048	525	565
9B	1,190		1,605			2,850			.16			.056		510	
9B	1,230	{1,430 (43) {1,395 (44)	1,720	910	{3,395 (43) {2,885 (44)	3,440	2,065	{.16 (43) {.17 (44)	.15	.16	{.042 (43) {.048 (44)	.050	.044	485	500
9B	1,270		1,930			3,655			.16			.053		475	
2C	1,155			325			390			.10			.083		980
2C	1,270			360			615			.24			.059		585
K	1,190			595			930			.15			.064		730
K	1,230			580			1,290			.16			.045		805
K	1,270			710			1,440			.16			.049		740
M	1,190			550			920			.21			.060		475
M	1,230			715			1,265			.21			.056		490
M	1,270			755			1,620			.24			.046		415

[1] The letter following the numeral refers to the series which contained these bodies. K and M are commercial bodies.

[2] Tested at room temperature.

[3] The numbers in parentheses following the values are the identification numbers of the clays used in the bodies and are referred to in preceding reports. The average results of tests of clays may be compared with the results for similar properties of the fine-grogged bodies heated at the same temperature, namely, 1,230° C. For example, the averages for clays 21 and 47 may be compared with the values for body 1B, fine grog, heated at 1,230° C. A similar comparison may be made with clays 24 and 32 and fine-grogged body 2A; also clays 43 and 44 and fine-grogged body 9B. These examples are given to show that the properties of a body compare favorably with the properties of the clays from which prepared. The sizes of the grog in the coarse-grogged blended-clay bodies were entirely different from those used in the simple-clay bodies; consequently the results would not be in agreement. In the case of the fine-grogged blended-clay bodies and simple-clay bodies the sizes of grog were not greatly different.

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(a) LINEAR THERMAL EXPANSION

Detailed expansion data will not be given in the present paper, since they have already been published.[9] Specimens prepared from a blend of 2 clays and grog made from the same 2 clays and heated at either 1,230 or 1,270° C were classed into 3 groups, depending on whether the expansion of the body was (1) greater than that of either of the constituent clays; (2) approximately equal to the average of that of the clays; or (3) approximately equal to the clay having the lower expansion. It was also found that the bodies prepared with the coarser sizes of grog showed, in the majority of cases, a lower expansion than those prepared with the finer sizes of grog. Results indicated, as a rule, that the blended clays would be more serviceable, as judged by expansion characteristics, for making saggers than the individual clays. The linear expansion of the bodies changed with temperature of heating, but such changes were not consistent either in direction or magnitude. Figure 2 shows the linear thermal expansion of several bodies and the constituent clays.

(b) YOUNG'S MODULUS OF ELASTICITY, TRANSVERSE STRENGTH, AND EXTENSIBILITY

Young's modulus of elasticity and the modulus of rupture were determined for the heated sagger bodies at 1,000° C in the majority of cases and at room temperature, and also at some intermediate temperature in all cases. The latter temperature corresponded to that at which saggers made from any one body failed in the thermal-shock test.

The modulus of elasticity of the sagger body is in general very close to the average of that of the clays contained in the body if prepared similarly. By proper selection of clay combinations and heating temperatures it was possible to vary the modulus of elasticity in the final group of laboratory-prepared bodies from 160,000 to 4,100,000 lb/in.^{2}. The modulus of elasticity was varied also by using grog of different sizes. In all cases the bodies prepared with the coarse grog had a lower modulus of elasticity than those prepared with the fine. The difference ranged from less than 10 percent to over 170 percent, but in most cases was between 50 and 100 percent.[10]

When tested at some one temperature between 350 and 900° C, the moduli of elasticity of the bodies were, with very few exceptions, greater than the values obtained at room temperature. The increase depended mainly on the type of clays composing the individual body and the temperature at which the body was tested. Some of the bodies showed an increase of less than 10 percent; others showed considerably in excess of 100 percent.[11]

Tests made at 1,000° C showed that the moduli were in most cases greatly below the values[12] obtained at room temperature. Thus, for example, if at room temperature the modulus of elasticity was 5,000,000 lb/in.^{2}, the modulus at 1,000° C would be only about one-tenth as much; while if the initial value was 1,000,000 lb/in.^{2}, it would drop to about one-third as much at the high temperature. There is no doubt that the glassy matrix, so effective in giving a high

[9] J. Am. Ceram. Soc. **9**, 554 (1926). See footnote 1.

[10] The modulus of elasticity values from which these percentages were drawn are given in tables 2 and 3, BS J. Research **3**, 419 (1929) RP104, and table 2 BS J. Research **7**, 1017 (1931) RP387.

[11] See footnote 10.

[12] See footnote 10.

modulus of elasticity at low temperatures, contributes very little, if any, to the modulus of elasticity at 1,000° C.

The transverse strength, expressed as modulus of rupture and computed from data obtained on the same specimens used in the tests for modulus of elasticity, was affected by the initial heating temperature,

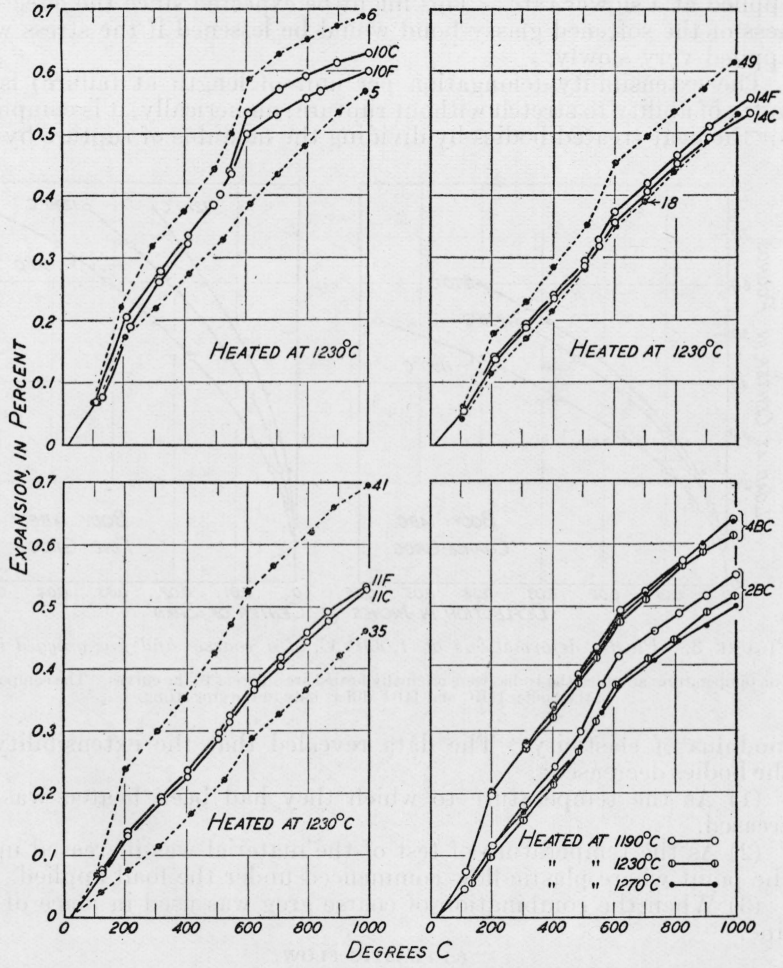

FIGURE 2.—*Linear thermal expansions of several bodies and also those of the constituent clays.*

The bodies in which comparatively fine or coarse sizes of grog were used are labeled with F and C, respectively. The curves in the lower-right portion of the figure show the expansions of 2 different bodies after having been heated at different temperatures.

grog sizing, and type of clay used in the same way as the modulus of elasticity was affected. For example, in the series of bodies in which both the type of clay and the heating temperature changed but only a combination of coarse grog was used, the modulus of rupture ranged from 120 to 2,050 lb/in.^{2} Another group of bodies selected from a series in which 3 different heating temperatures and 2 different combinations of grog sizes were used, but no change was made in the clays

of any one group, showed a range in modulus of rupture from 800 to 2,000 lb/in.[2] When tested at temperatures ranging between 350 and 1,000° C the modulus of rupture is generally greater than at room temperature. Because the tests at 1,000° C were made by rapidly increasing the load until rupture of the specimen occurred, the results are probably higher than would have been the case had the load been applied at a slower rate. This might be expected since the effectiveness of the softened glassy bond would be lessened if the stress were applied very slowly.

The extensibility (elongation per unit of length at failure) is an index of ability to stretch without rupture; numerically, it is computed for the heat-treated bodies by dividing the modulus of rupture by the

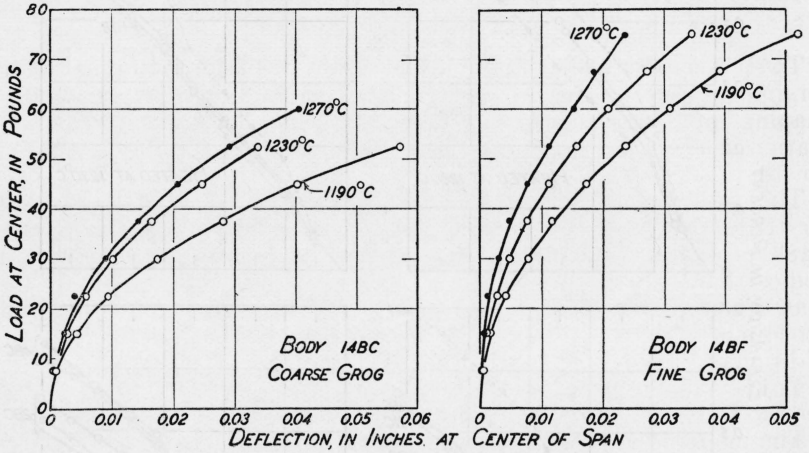

FIGURE 3.—*Plastic deformations at 1,000° C, of a coarse- and fine-grogged body.*

The temperatures at which the bodies were originally heated are adjacent to the curves. The composition of the bodies 14BC and 14BF differs only in the grog sizing.

modulus of elasticity. The data revealed that the extensibility of the bodies decreased:

(1) As the temperature to which they had been heated was increased.

(2) As the temperature of test of the material was increased up to the point where plastic flow commenced under the load applied.

(3) When the combination of coarse grog was used in place of the fine.

(c) PLASTIC FLOW

Measurements of plastic deflections were made at 1,000° C only and the results obtained, which apply only within the limits of preheating temperatures and grog sizes used, may be summarized as follows:

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

(2) The plastic flow decreases with increase of initial heating temperature of the specimens. The data in this connection indicate the undesirability of placing heavy loads in or on saggers which have not been preheated sufficiently.

(3) The percentage increase in plastic deflection of different bodies was not proportional to the change in load when the applied load was increased 100 percent.

(4) With bodies high in flux, the plastic deflection is directly proportional to the silica-alumina ratio. On the other hand, bodies high in silica and low in flux have a low plastic flow.

The plastic flow (time-deflection) of 16 simple clay bodies under a constant load of 30 lb./in.^{2} for ½ hour ranged from less than 0.0001 to 0.0005 in., and for 18 bodies from less than 0.0001 to 0.002 in.

Six curves illustrating the total plastic deflection of 2 blended clay bodies heated at different temperatures are given in figure 3. The data were taken from the load-deflection curves obtained for the body at 1,000° C.

3. COMMERCIAL BODIES

Twelve commercial bodies furnished by 10 plants manufacturing ceramic products were received in the plastic condition ready for shaping into test specimens. Tests of these bodies divulged information relative to the properties of sagger mixes actually prepared for use in service.

The total linear thermal expansion from 20 to 250° C was high for the majority of the bodies. The mean value for 11 mixes was 0.186 percent, which indicates a greater expansion in commercial bodies than is thought necessary because laboratory tests indicate that, by proper blending, clay bodies having lower expansion, and hence more desirable properties, can be made without much, if any, additional difficulty.

Young's modulus of elasticity ranged from 665,000 for a body heated at 1,190° C to 3,160,000 lb./in.^{2} for one heated at 1,270° C.

The modulus of rupture ranged from 665 lb./in.^{2} for a body heated at 1,190° C to 1,415 lb./in.^{2} for one heated at 1,270° C.

The extensibility, based on the mean values for Young's modulus and modulus of rupture, was 0.056 percent, which is about midway between the highest value (0.0834 percent) and the lowest value (0.0277 percent) obtained for the final group of experimental laboratory bodies.[13]

The mean plastic flow of the commercial bodies at 1,000° C. when stressed at approximately 120 lb./in.^{2} for 1 hour was 0.000275 in.

The results for the commercial bodies are typified by the values for bodies K and M in table 2.

VI. EFFECT OF TALC ON SOME PROPERTIES OF SAGGER BODIES

It is not surprising that manufacturers using talc-containing sagger mixtures reported difficulties due to excessive bulging of sagger bottoms. Such bulging could readily be attributed to lowered refractoriness of the mix because talc increased the plastic flow by increasing the percentages of low-fusing glasses.

Magnesium oxide is the constituent of the talc believed to be mainly accountable for both the added good qualities of the sagger as well as those which would be considered detrimental. The brief study undertaken in this connection therefore included commercially

[13] J. Am. Ceram. Soc. **16**, 601 (1933).

prepared sagger bodies containing magnesium oxide added either as talc or as magnesite. The talc was of the lime-bearing variety from northern New York, containing about 30.5 percent magnesium oxide and the magnesite was of the Grecian variety.

TABLE 3.—*Some properties of a commercial sagger body showing the effect of added talc or magnesite*

Body no.	Magnesium oxide added as—		Absorption	Pyrometric cone equivalent (pce)		Total linear thermal expansion 20° C [1] to—			Tested [2] at 20° C			Tested [2] at 625° C		Deformation [3] at 1,200° C
	Talc	Magnesite				250° C	600° C	1,000° C	Modulus of rupture	Modulus of elasticity	R/E	Modulus of rupture	Modulus of elasticity	
	%	%	%	Cone	Approx. °C	%	%	%	lb/in.²	1,000 lb/in.²		lb/in.²	1,000 lb/in.²	Inch
1	0	0	15.1	27–28	1,610	0.23	0.46	0.59	630	1,125	0.000563	750	1,435	0.0710
2	5	0	13.9	18–19	1,500	.15	.32	.46	480	556	.000858	710	1,457	.0620
3	0	5	15.0	20–23	1,550	.14	.32	.47	510	527	.000977	820	1,441	.0235
5	0	2.5	14.5	26	1,595	.18	.38	.52	470	617	.000775	790	1,345	.0230
6	2.5	0	14.2	23	1,580	.19	.39	.53	610	766	.000804	790	1,456	.0390

[1] Room temperature considered as 20° C in all tests.
[2] Average of 2 tests in all cases.
[3] Total deformation after 2½ hours at 1,200° C and a constant load of approximately 6 lb/in ². The specimen (1 by 1 by 9 in.) was placed over an 8-in. span and the load was applied at midspan.

The results of all tests made are given in table 3. Although the number of test specimens was limited, the results show clearly the effects of the added talc or magnesite on the properties of the sagger body. For example, the refractoriness of the original body, as indicated by the pyrometric cone equivalent, was reduced from 1½ to 5 cones (15° to 110° C), the talc-containing bodies showing the greater change. The total linear thermal expansion was also reduced, but the reduction was approximately the same with either talc or magnesite. The extensibility of the body measured at room temperature and the plastic deformation measured at 1,200° C increased with increase in talc or magnesite content. The results show that the addition of a small percentage of magnesium oxide, either as talc or magnesite, to clay sagger bodies is beneficial both with respect to resistance to thermal shock and plastic deformation. The resistance to thermal shock may be attributed primarily to the decided reduction in the thermal expansion of the body and secondarily to the increased extensibility or stretch of the body before rupture. Any beneficial effect a small percentage of talc or magnesite may have in reducing the plastic flow is dependent on the temperature at which the saggers are used. For instance, as shown in table 3, the deformation obtained with specimens tested at 1,200° C was lower when they contained talc or magnesite than when they were free from either. When tested at 1,250° C (the data for which are not given, because of unsatisfactory end points), the 2 bodies containing talc failed because of plastic flow much sooner than the same body free from talc. The bodies containing the magnesite did not rupture during the 2½-hour test made at 1,250° C. However, in comparison with the data obtained at 1,200° C, the body containing 2.5 percent of magnesite

deformed twice as much at 1,250° C and that containing 5 percent deformed 4 times as much.

Since magnesia has such a detrimental effect on the refractoriness of clay, and this in turn is the cause of decreased resistance to plastic deformation, grog made from talc-containing saggers must be used with precaution. If the amount of magnesia in the grog is not taken into consideration when talc is added to a sagger body, it would be only a comparatively short time before the sagger mix would have little value. Actual plant records on the 2.5-percent-talc body in comparison with the talc-free body (records are not available on the other mixtures) indicated the latter had approximately one-half the service life of the former.

VII. DISCUSSION AND APPLICATION OF RESULTS TO PREDICTION OF SAGGER LIFE IN SERVICE

The two most important properties affecting the life of the sagger from the standpoint of resistance to thermal shock are believed to be thermal expansion, and extensibility or maximum strain. Since plastic flow (cause of bulging of sagger bottoms) is also an important factor in the life of saggers, it was given some study. Although conductivity is undoubtedly of some importance in connection with the resistance of clay saggers to thermal shock, no measurements of this property were made. Consequently any conclusions relative to sagger life as affected by thermal shock are based on data obtained in tests for thermal expansion, Young's modulus of elasticity, and modulus of rupture. These properties give information relative to resistance to mechanical stress (that is, modulus of rupture) and also relative to resistance to thermal shock (that is, $\frac{\text{modulus of rupture}}{\text{modulus of elasticity}}$, together with thermal expansion). In order that the manufacturer of saggers may conveniently apply the information obtained so as to produce saggers of desired quality, a chart (fig. 4) has been prepared based on those three properties determined for 73 different bodies. In this chart, T, as previously defined, is the temperature from which the sagger was quenched when fracture occurred, and is used as a measure of the resistance to thermal shock.

In the final phase of the investigation [14] a series of 12 bodies were prepared in which the information given in the chart served as a guide in predicting the service life of the saggers from the standpoint of resistance to heat shock. This was accomplished by testing the clays which it was intended to use in any one body and the approximate resistance to thermal shock was predicted by locating the mean values on the chart. Heat-shock tests were then made and the results agreed satisfactorily with the predicted life. From this it may be concluded that, if the manufacturer of saggers determines the properties of the clays after heating at the approximate temperature at which they will be used, he can readily predict the relative life of the sagger prepared from those clays by referring to the chart.

The chart shows to the manufacturer how certain important physical properties may affect the life of saggers. For instance, an examination of the left side of the figure shows that, for saggers having the same total expansion from 20 to 250° C, those having the greatest

[14] J. Am. Ceram. Soc. **16,** 601 (1933).

resistance to thermal shock have both a comparatively low modulus of rupture and a low modulus of elasticity. As the lower left-hand corner is approached, both strength and modulus of elasticity increase, but unfortunately the latter increases at a much greater rate than the former. This means that the ultimate "stretch" or extensibility before rupture, is decreasing rapidly, which in turn causes the saggers to have a lower resistance to thermal shock T. The values of T, obtained by subjecting experimental saggers to thermal shock in an air-quenching test, should be considered only relative because their

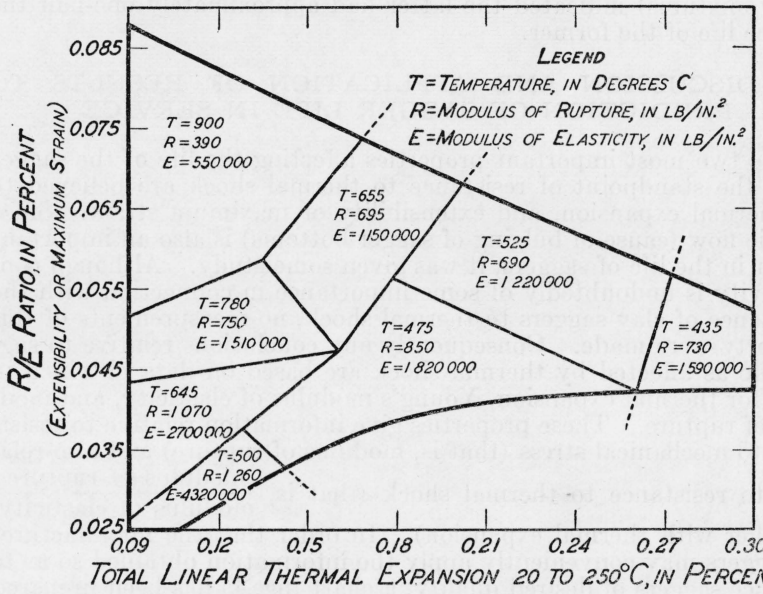

FIGURE 4.—*Areas showing the trend of the relation between resistance of saggers to failure due to thermal shock, and linear thermal expansion and extensibility.*

For all bodies included in each area are given the average values for modulus of rupture and modulus of elasticity determined at room temperature, and also the temperature T from which the saggers were quenched when fracture occurred. The trend of the values for T is considered as the trend of the resistance of sagger bodies to heat shock. The values in each area represent the mean of numerous determinations which more or less blend from one area to the adjoining ones. No sagger bodies were made which fell outside the areas bounded by the heaviest lines. The average values in the several areas for modulus of rupture and modulus of elasticity are given to illustrate that if the thermal expansion is kept constant, strength is obtained only at the expense of the extensibility because the modulus of elasticity increases at a much faster rate than the modulus of rupture.

magnitude will depend, among other things, on either the percentage or sizes of grog in the body or both and also whether the grog is vitreous or porous. As is evident from the chart, however, the determination of T by a manufacturer of saggers is not essential since the several areas always bear the same relation to one another and the location of a sagger body on the chart is determined by its R/E and thermal-expansion values, and its relative location gives an indication of its quality.

Based on our laboratory-prepared bodies it is believed that the most satisfactory sagger bodies for general purposes have the properties given in the area at the left side of the chart where T equals 780, R equals 750, and E equals 1,510,000. The modulus of rupture

of 780 is believed to be sufficient because it compares favorably with that of 12 commercial sagger bodies.

Results obtained in laboratory tests of 12 plant or commercial bodies showed 6 to have properties which placed them in the area (fig. 4) where T is 475, 3 where T is 525, and the other 3 in the area where T is 655. As far as data are available for the plant life of saggers on which laboratory tests were made they indicate that saggers having properties in the range between 0.15 to 0.18 percent for linear expansion, and 0.45 to 0.65 percent for extensibility gave the most satisfactory service. In 3 commercial plants increased life was actually obtained by shifting to the properties toward the left and top of the graph.

VIII. SUMMARY AND CONCLUSIONS

Fifty-one clays used for sagger making and representing mining districts in New Jersey, Kentucky, Ohio, Tennessee, California, Georgia, Illinois, Pennsylvania, and South Carolina were used in this investigation. A total of 85 bodies were prepared and tested in the laboratory. In these bodies 2 different series of grog sizes were used (i. e., 1 series of comparatively coarse and the other of comparatively fine sizes of grog) and 6 different heating temperatures. In addition, 17 sagger bodies used in commercial practice were tested. Two of these bodies contained talc, 2 magnesite, and another of the same clay and grog composition as the preceding 4 was free from either talc or magnesite.

The chemical compositions and pyrometric cone equivalents of the clays, and the results of such tests of the physical properties of both clays and bodies as shrinkage, porosity, modulus of rupture, Young's modulus of elasticity, linear thermal expansion, plastic deformation, and resistance to thermal shock were reported in detail in preceding reports. In this report reference is made only to extreme values.

From data obtained in the entire investigation a chart was prepared, which it is believed will permit the manufacturer of saggers to predict with a reasonable degree of accuracy the relative length of service which may be expected from saggers made from combinations of clays of which some of the properties have been determined.

Among the conclusions drawn from the results obtained the following are thought to be the most significant:

(1) Any sagger body having a total linear expansion from room temperature to 250° C of approximately 0.18 percent or greater cannot be expected to have a high resistance to thermal shock.

(2) The life of the sagger is more sensitive to changes in thermal expansion than to changes in the extensibility or "stretch" of the sagger body.

(3) There is no relation between changes in modulus of elasticity and porosity. Great increases in this molulus may accompany changes in grog sizes from coarse to fine, or higher temperatures of heating, with very little change in porosity.

(4) Bodies containing porous grog are more resistant to thermal shock than bodies containing dense or vitreous grog.

(5) Angular and loosely bonded grog particles in a body result in a high extensibility or stretch of that body, which in turn gives the body increased resistance to heat shock.

(6) The plastic deformation at 1,000° C is less in fine-grogged bodies than in coarse-grogged and decreases with increase of heating temperature. Also, the flux content is an important factor in causing plastic deformation and is more serious if the silica content is high.

(7) The addition to a sagger body of magnesia either as talc or magnesite will lead to increased sagger life, but care must be taken to control the quantity present, since both the refractoriness and plastic deformation may be affected detrimentally if too much magnesia is present.

(8) It is very desirable, and should prove profitable for the manufacturer, to analyze the conditions of service under which his saggers are to be used. In most cases it is impossible to prepare, from the ordinary sagger clays, bodies which have properties ideally suited for long life in all types of service. Therefore, by knowing certain properties of the clays and grogs available, only those suitable for his service would be used for making sagger bodies.

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