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EFFECT OF THE SIZE OF GROG IN FIRE-CLAY BODIES

BY

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By F. A. Kirkpatrick

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I. INTRODUCTION

In those industries which use crushed and ground raw materials in forming bodies by means of a cementing action of some sort the size of the particles plays a most important rôle. This may be in many instances the main factor controlling the desired properties in the body. This is nowhere more true than in the ceramic industries, where in compounding bodies the manufacturer is compelled to use materials from the size of pebbles down to the dispersoid and emulsoid (colloidal) states. All present evidence tends to show that in disperse systems the size of particles which we can not now measure has as much effect upon the properties of certain materials as have the larger sizes which we are able to measure. In no other way is it possible to account for the great

differences in cementing power exhibited by fine-grained bond clays and other fine-grained materials. In practice the cementing action takes place at temperatures from zero to that of the electric arc, depending upon the nature of the process, and is due to many different chemical reactions. In the present work the bonding power of mixtures composed of raw clay and calcined clay is determined after these bodies have been heated to 110° C and to 1250° and 1300° C.

II. LITERATURE

The literature upon this subject is confined mostly to investigations of mortars and concretes. Rene Feret, chief of the Laboratory of Bridges and Roads at Boulogne-sur-Mer, France, has made an extensive investigation of the effect of the size of grain of sand upon the properties of cement mortars.[1] In this work the sands were separated into three sizes as follows:

Designation	Range of size of particles	Approximate screen sizes, Tyler standard
	Inch	Mesh
G	0.20 –0.079	4–10
M	.079– .02	10–30
F	.02 –dust.	30–dust

These three sizes were combined in all possible proportions and made up into Portland cement mortars and various properties determined. The results were shown graphically by means of triaxial diagrams as illustrated in Fig. 1. The lines within the triangle were drawn through points representing mortars having the same strength. The strongest bodies contained sand of about 80 parts *G*, 20 parts *F*, and a small amount of *M*. It should be noted that Feret worked with mortars only and not with concretes

Fuller and Thompson [2] have studied the effect of the size of materials on concrete, where the conditions are different from those in mortars. They recombined the different sizes of materials, not by means of triaxial diagrams but by the use of analysis curves. By this method any number of different sizes can be accurately combined to form a mixture of any desired granular composition. One of the most important conclusions was that concrete having

[1] Sur la compacité des mortiers hydrauliques, Annalen des Ponts et Chaussees, Memoires et Documents, 4, pp. 1–164; 1892–2.

[2] The Laws of Proportioning Concrete, Trans. Amer. Soc. Civil Engrs., 59, p. 67; 1907. Also Concrete Plain and Reinforced, Taylor and Thompson.

the highest density and highest strength possessed an analysis curve which consisted of an ellipse and a straight line or of a parabola. The method is illustrated in Fig. 2. The curve designated "Parabola" is the analysis curve of the strongest concrete. Materials Nos. 1, 2, 3, and 4 have been so combined that the mixture has a curve very close to the parabola, as indicated by the dotted line.

After an extended investigation, Wig, Williams, and Gates[3] concluded that the law of greatest strength given by Fuller and

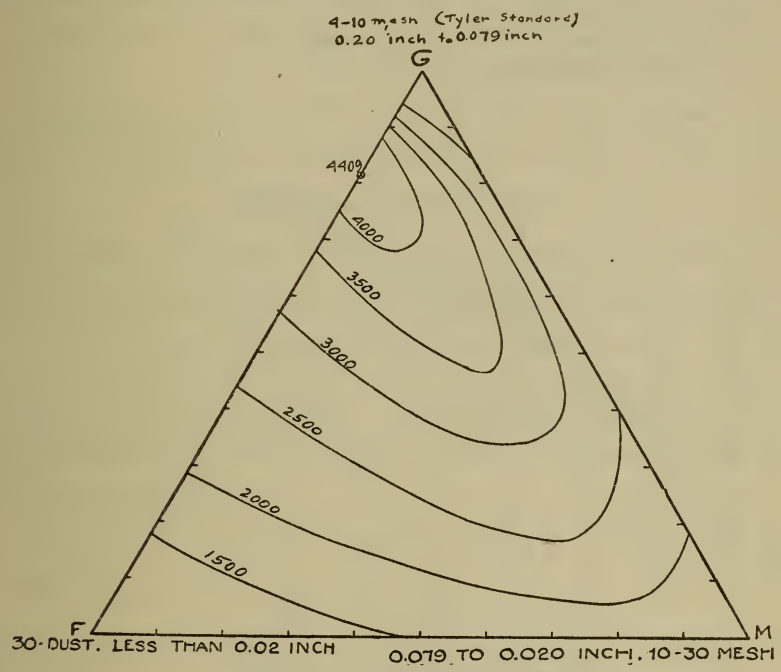

FIG. 1.—*Relation between size of sand and compressive strength in pounds per square inch of 1:3 (by weight) mortars after nine months in air and three months in sea water. After Feret. From Concrete Plain and Reinforced (p. 146), Taylor and Thompson*

Thompson is not general and that there exists no maximum curve applicable to all concretes and mortars.

It should be noted that the results of the above investigations could be expected to throw light upon the question of the size of grain in fire-clay bodies in the unburned state only, since in the burned state other factors, such as fusion or vitrification, exert the controlling influences upon the properties.

The recorded work on the effect of fineness of materials on the properties of bodies in the burned state has to do mostly with

[3] Strength and Other Properties of Concrete as Affected by Materials and Methods of Preparation, B. S. Technologic Paper No. 58

vitreous products as porcelain, china, etc. The effect of the size of grog in fire-clay bodies, however, was studied by Fulton and Montgomery [4] using bodies made up of 50 per cent St. Louis fire clay and 50 per cent grog by weight. They prepared five sizes of grog, using all material passing through the sieves of 6, 14, 35, 100, and 200 mesh. They found that the modulus of rupture in the raw state increased from 6 to 100 mesh grog, then decreased with 200 mesh, showing that the very fine nonplastic gave a low strength. In the burned state, strength increased with decrease of grog size up to cone 15. At this temperature, porosities of 6, 14, and 35 mesh bodies were 10 to 13 per cent, while those of 100 and 200 mesh bodies were 5 to 6 per cent.

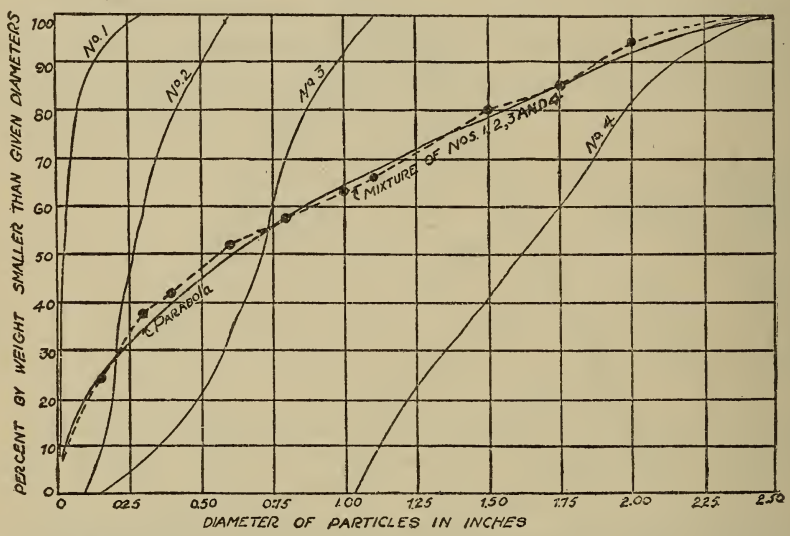

FIG. 2.—*Method of proportioning a graded mixture. From Concrete Plain and Reinforced (p. 786), Taylor and Thompson*

In view of the fact that so little work had been done along this line, it was considered advisable to undertake an investigation of the effect of the size of grog on some properties of fire-clay bodies. On account of the fact that the grog could be separated into a great many portions of different sizes and recombined in an infinite number of proportions, the present work could hope to cover only a limited field of practical grog sizes.

This work was begun by G. H. Brown and H. G. Schurecht in 1915 and completed by the writer in 1916–17 along the same lines as originally planned. Although the investigation was intended as a study of sagger bodies, a more general application of the results can be made.

[4] The Effect of Grog in Fire Clay Bodies, Trans. Amer. Cer. Soc., 17, p. 409

III. METHODS

1. GENERAL PLAN

The general plan of procedure consisted of the separation of grog into different sizes, recombining these in arbitrary proportions, adding an equal weight of plastic fire clay and molding into small bars for testing. As stated in the introduction, there are two principal methods of recombining the separated portions—first, by means of triaxial diagrams; second, by means of analysis curves. The first method was adopted, since it was obvious that the second would be of value only for bodies in the raw state. Strength in the burned state increases with surface factor below the temperature where overburning begins and the analysis curve for maximum strength would be a straight line perpendicular to the size axis at the ordinate representing the smallest size obtainable.

2. PREPARATION OF GROG

The grog was made by crushing high-grade fire brick, which was composed of about 50 per cent flint fire clay, in a wet pan. The grog was screened through sieves with a power shaker and separated into the following sizes: 4 to 8 mesh, 8 to 12, 12 to 20, 20 to 40, 40 to 80, 80 to dust. Each sized portion was thoroughly mixed by means of shoveling. Mechanical analyses were made of each portion with Tyler standard screens. The sizes of the screens used were as follows:

Mesh	Size of opening	Mesh	Size of opening	Mesh	Size of opening
	Inch		Inch		Inch
4	0.200	14	0.046	80	0.0069
6	.131	20	.033	150	.0041
8	.093	30	.0198	200	.0029
10	.072	40	.0150	300	.0017
12	.054	60	.0087		

The analyses of the separate portions were as follows:

Mesh of screen	Mesh of screen	Per cent passing	Mesh of screen	Mesh of screen	Per cent passing
4–8	4–6	49.4	40–80	40–60	52.7
	6–8	50.6		60–80	47.3
8–12	8–10	36.9	80–dust	80–150	37.4
	10–12	63.1		150–200	15.8
12–20	12–14	26.6		200–300	19.0
	14–20	73.4		Through 300	27.8
20–40	20–30	44.8			
	30–40	55.2			

3. PREPARATION OF BODIES

All bodies were of the composition 50 per cent grog and 50 per cent clay by weight. The clays were ground to pass a 20-mesh screen. The bodies were made up in seven triaxial series having the following grog components and clay composition:

Series number	Size of grog (mesh)	Clay
1	4–8, 8–12, 12–20	Plastic fire clay.
2	8–12, 12–20, 20–40	Do.
3	12–20, 20–40, 40–80	Do.
4	20–40, 40–80, 80–dust	Do.
5	4–20, 20–80, 80–dust	Do.
6	4–20, 20–80, 80–dust	Equal parts plastic fire clay and Georgia kaolin.
7	4–20, 20–80, 80–dust	Illinois kaolin.

The 4 to 20 mesh grog was composed of equal parts of 4 to 8, 8 to 12, and 12 to 20 sizes. The 20 to 80 grog was made up of equal parts of 20 to 40 and 40 to 80 sizes. Each series contained 16 bodies designated by letters and having the grog composition shown in Table 1.

TABLE 1

Letter	Per cent A	Per cent P	Per cent M	Letter	Per cent A	Per cent P	Per cent M
A	100	.....	.....	I	33⅓	66⅔	.....
B	66⅔	.....	33⅓	J	20	20	60
C	66⅔	33⅓	.....	K	20	40	40
D	60	20	20	L	20	60	20
E	40	20	40	M	.....	.....	100
F	40	40	20	N	.....	33⅓	66⅔
G	33⅓	.....	66⅔	O	.....	66⅔	33⅓
H	33⅓	33⅓	33⅓	P	.....	100	.....

The clay and grog were thoroughly mixed dry by shoveling and pugged in a wet pan. The plastic mass was left standing at least two hours to allow the grog to absorb moisture. Briquettes 1 by 1 by 7 inches were molded by hand in a brass mold. This size was chosen because it had proved satisfactory for similar tests. The use of several sizes would have been too time consuming. Moreover, the results obtained would themselves determine whether or not the proper size had been used.

4. PROPERTIES OF RAW BODIES

Two properties of the mixtures in the raw state were determined—strength and porosity. Modulus of rupture was chosen as a measure of strength, since this was found by Bleininger and

Howat[5] to give more uniform results than compressive or tensile-strength. Merriman's discussion of beams in Mechanics of Materials shows that bars under transverse load are subject to forces of shear, tension, and compression and that the values of modulus of rupture, or flexural strength, lie between those of tensile strength and compressive strength. Thus the modulus of rupture results from a combination of these three forces, and for our present purpose gives a better all-around idea of strength than any one of the three. For these determinations, briquettes were air-dried at least three days, dried at 65° C for one day, and finally at 110° C for two days. They were broken in the transverse test machine described by the above writers.

The formula used for calculation of the modulus of rupture was as follows:

$$M = \frac{3\,Fl}{2\,bd^2}, \text{ where}$$

M = modulus of rupture in pounds per square inch;
F = force applied in pounds;
l = length between supports in inches;
b = width of bar in inches;
d = depth of bar in inches.

The distance l was 5½ inches; b and d were each about 1 inch, and were measured to hundredths of an inch. Seven bars of each mixture were tested and the average modulus of rupture calculated.

For the determination of porosity, briquettes were dried at 110° C for 1 day, weighed, immersed in kerosene, and placed in a cylinder under reduced pressure (about 0.2 atmosphere) for 12 hours. They were then weighed suspended in kerosene and in air. Four test pieces of each body were used.

5. PROPERTIES OF BURNED BODIES

For the determination of properties in the burned state, briquettes were given three different heat treatments: Cone 10, 1200° C; cone 12, 1250° C; cone 14, 1300° C. A gas-fired test kiln was used, the rate of rise of temperature being 25° C per hour. The final temperature was maintained for 2 hours.

The properties of the burned bodies determined were strength, porosity, volume shrinkage, and resistance to sudden temperature

[5] The Compression, Tensile and Transverse Strength of Some Clays in the Dry State, Trans. Amer. Cer. Soc., **16**, p. 273.

changes. The modulus of rupture was used as a measure of strength. In order to decrease the time consumed in laboratory work, the 3½-inch pieces obtained by breaking the raw bars were used in the burned state for these tests with a 2-inch span. The bars were broken in a 10 000-pound hand-power Olsen machine and the modulus of rupture calculated in the same manner as given for raw bodies. The question has arisen as to whether the 2-inch length of span is too short and the values obtained for modulus of rupture too high due to their including a proportion of the shearing strength, which may be higher than flexural strength. In the absence of sufficient evidence no conclusion can be reached. It may be of interest to note that Fulton and Montgomery in the work quoted in footnote 4 (p. 6), using St. Louis fire-clay bodies and a 4-inch span, obtained values of modulus of rupture up to 6622 pounds per square inch, while the highest in the present work was 5373 pounds per square inch for the 80 to dust grog body. A standard size of bar should be used for this work. Bars 1 inch square and long enough for a 4 or 6 inch span have proven satisfactory. In regard to the results here presented, it may be said that they afford a sufficiently accurate means of comparison of strength of the bodies. The average difference from the mean value was about 10 per cent, as low a value as could be expected for fire-clay bodies.

Determinations of porosity were made in the same manner as for the raw bodies, except that water was used instead of kerosene. Volume shrinkage was determined by measuring the volume of the test pieces in a volumenometer before and after burning. Two briquettes of each kind were used.

In order to determine the loss of strength due to sudden temperature change, briquettes previously burned to cone 12 were heated five times to 600° C and quenched in ice water after each heating. Six test pieces of each kind were used. The modulus of rupture was then determined with a 2-inch span. The strength after treatment expressed as a percentage of that before treatment afforded a means of comparison of the value of the bodies in repeated heating.

Some manufacturers who use refractory brick for checkerwork demand that these brick shall not fail upon being heated 30 times to 1000° C and quenched in cold water for 1 minute after each heating. On account of the importance of this test, it was desired to determine the effect of the size of grog upon the dura-

bility of bodies subjected to such treatment. Bars 1 by 1 by 7 inches previously burned to cone 12 were heated in a gas furnace to 1000° C in from 2 to 4 hours and quenched in running water at about 15° C after each heating. The bars were immersed for 15 seconds. After this length of time they were still at a red heat in the center and absorbed no water; hence, were perfectly dry when replaced in the furnace. The number of treatments which the bars withstood before breaking in two was used as a means of comparison of their durability under the conditions of the test. The broken pieces were reheated many times, but a criterion of final failure could not be devised for such small pieces and no results of value were obtained.

IV. RESULTS OF TESTS UPON BODIES CONTAINING ONE SIZE OF GROG

Before studying the results obtained by recombining the grog portions, it will be of interest to examine the data for bodies containing the single sizes. In Fig. 3 is shown the relation between temperature of burning and porosity of these bodies and of the clays. The corresponding values are given in Table 2. The method of making these determinations and the meaning of the curves is given on page 12 of this Bureau's Technologic Paper No. 79, by Bleininger and Schurecht on European Plastic Fire Clays. It is sufficient to repeat that the amount of pore space and the rate of change of this amount in burning are accurate indications of the vitrification temperature range, of the temperature of overburning, and hence of the refractoriness of the materials.

TABLE 2

Porosity of Clays and Bodies

Temperature, °C	Fire clay	Georgia kaolin	Grog body					
			4–8	8–12	12–20	20–40	40–80	80–dust
1150	27.70	45.30	25.72	26.70	27.85	29.20	29.75	29.72
1200	20.19	44.70	24.81	25.20	27.15	28.03	29.40	28.53
1230	14.08	39.28	23.59	24.43	26.50	26.65	27.90	26.63
1260	11.32	32.90	22.45	22.87	25.35	25.90	26.75	24.01
1290	9.58	29.48	22.40	22.80	24.35	24.10	26.12	23.25
1320	7.65	21.60	21.08	21.90	22.85	22.95	25.23	20.45
1350	4.19	19.05	17.75	18.60	19.05	18.90	21.21	14.75
1380	1.70	15.75	16.88	18.50	17.96	17.35	19.70	10.65
1410	1.41	15.88	16.24	17.49	17.62	16.90	17.90	10.51
1440	2.69	14.48	15.35	17.09	16.91	15.50	16.27	8.36

As the curves of Fig. 3 show, the bodies possess quite different rates of vitrification. At 1150° C the porosity of all the materials was from 25 to 30 per cent with the exception of the Georgia kaolin, which was 45.3 per cent. These are characteristic values

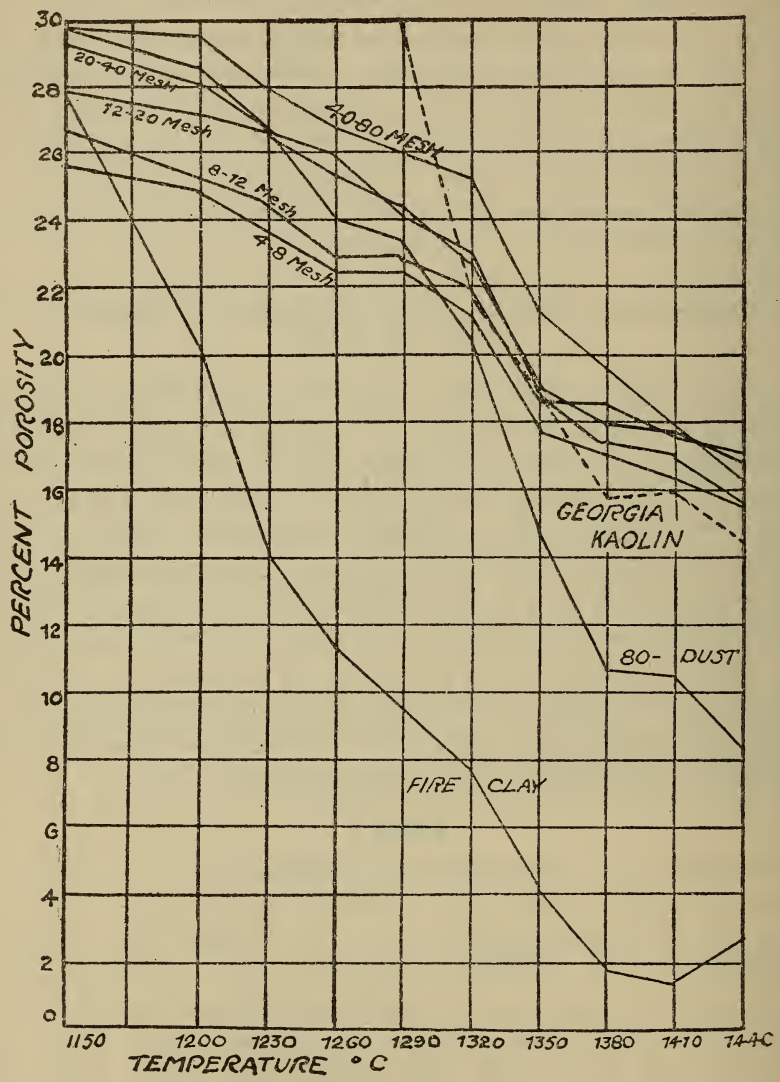

FIG. 3.—*Relation between porosity and temperature of burning of clays alone and of bodies containing grog*

for the types of clays represented. The Georgia kaolin had a high rate of vitrification below 1380° C at which temperature its porosity was only a little lower than that of the fire-brick bodies. Hence, when added to fire-brick mixtures the kaolin decreases the strength,

since it decreases the amount of fused or vitrified material in the brick. The fire clay had an average rate of decrease of porosity amounting to 5.1 per cent per 30° from 1150° C to 1230° C and 2.5 per cent per 30° from 1230° C to 1380° C. At 1380° C overburning began, due to the formation of a vesicular structure.

The addition of an equal weight of grog of any of the sizes indicated from 4 to 8 mesh to 40 to 80 mesh lowered the rate of decrease of porosity to an average of about 1.25 per cent per 30° C. That is, the refractoriness of the clay-grog bodies was much greater than that of the fire clay and the effect of overburning was eliminated. It is noted, however, that at the higher temperatures the 40 to 80 mesh body has a somewhat higher rate of vitrification and the 80 to dust body a much greater rate than have bodies containing coarser grog. In fact, the rate of decrease of porosity for the 80 to dust body from 1320° C to 1380° C was twice that of the fire clay; that is, the 80-mesh grog formed a dividing line between the coarse or slowly vitrifying and the fine or rapidly vitrifying grog in bodies made up with this especial fire clay. The fine grog offered more surface per unit volume for heat absorption and consequent fusion, and for solution by the fused portion of the clay. Another point of special interest is the fact that all of the curves except that for Georgia kaolin indicate a higher rate of vitrification between 1320° C and 1350° C than on either side of these temperatures. This may indicate the temperature at which a eutectic mixture begins to fuse. Stated in cones, the above range is approximately that from cone 12 to cone 14, since the draw-trial burn consumed less time than the other burns. As will be seen later, there was a great increase in strength of the bodies from cone 12 to cone 14, corresponding to the larger decrease in porosity within this range of heat treatment.

In Fig. 4 is given the strength-porosity curve for raw bodies. From 4 to 8 mesh to 40 to 80 mesh grog, strength increased with increase of porosity, this being due probably to cracks developed in drying. The size of the cracks decreased with decrease in size of grog. From 40 to 80 mesh to 80 to dust, strength decreased in the usual order with increase of porosity.

In Fig. 5 is shown the relation between surface factor and modulus of rupture in the raw and burned states. The surface factor was calculated according to the method suggested by Purdy [6] and includes the grog portion only. The strength

[6] The Calculation of the Comparative Fineness of Ground Materials by Means of a Surface Factor, Trans. Amer. Cer. Soc., 7, p. 441.

increased with increase of surface factor and with increase of temperature. As Fig. 6 shows, porosity in the raw and burnt

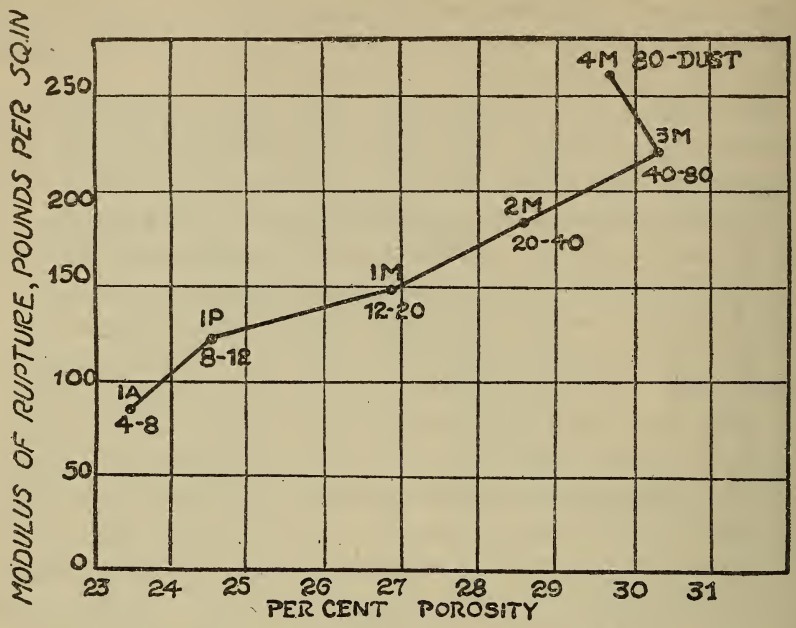

FIG. 4.—*Relation between porosity and modulus of rupture of raw bodies*

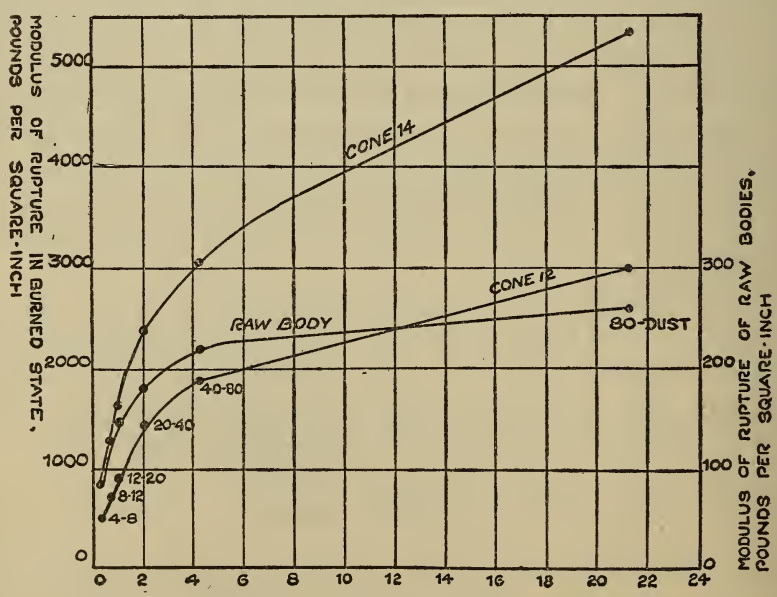

FIG. 5.—*Relation between surface factor and modulus of rupture*

states was a maximum in the 40 to 80 mesh body. The results from the quenching tests are given in Fig. 7. Bodies containing

the larger sizes of grog withstood the test best. The results for the single grog sizes are presented here briefly as a convenient

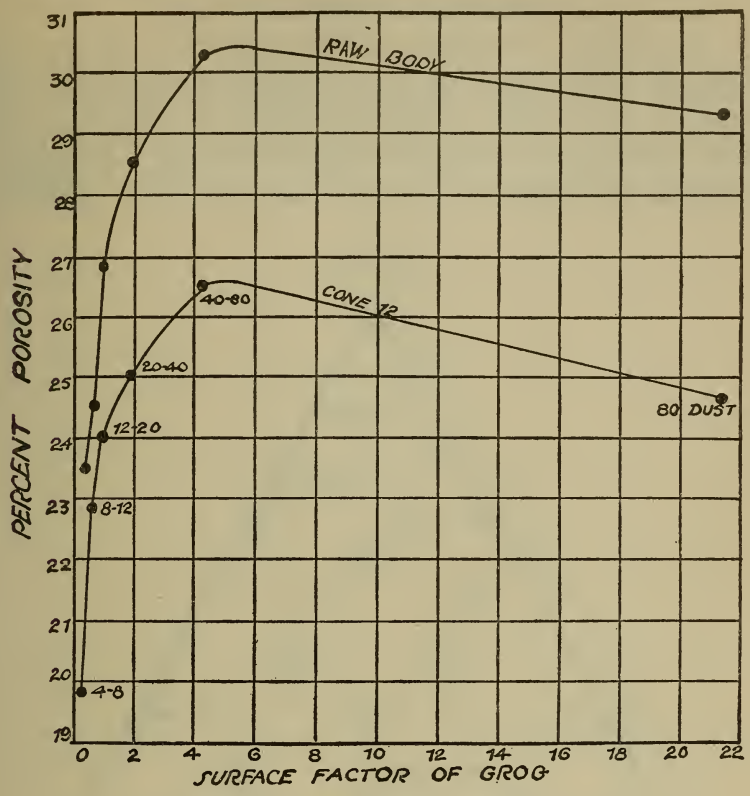

FIG. 6.—*Relation between surface factor and porosity*

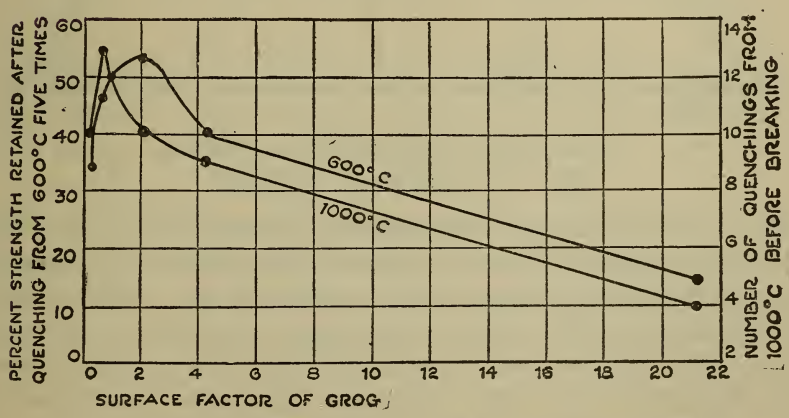

FIG. 7.—*Relation between surface factor and results of quenching tests*

means of comparison and will be included in the more detailed discussion of mixtures to follow.

V. RESULTS OF TESTS UPON BODIES CONTAINING MIXTURES OF GROG SIZES

1. PROPERTIES IN THE RAW STATE

(*a*) *Explanation of Diagrams.*—The single sizes of grog were recombined and made up into bodies as described under "Methods." Figs. 8 to 14 show the relation between grog composition and modulus of rupture of the raw bodies. This method of graphical representation of results may be briefly explained as

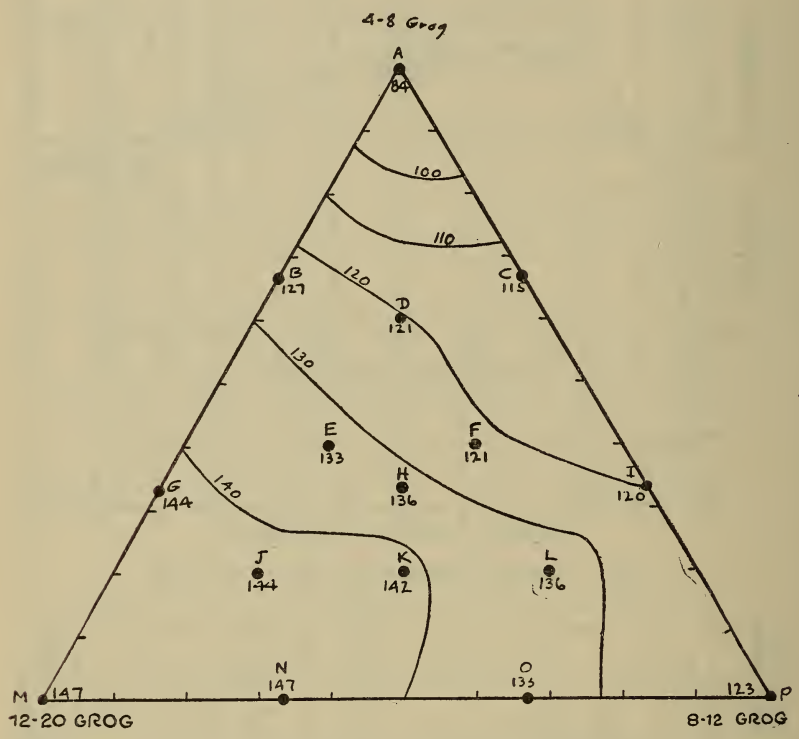

FIG. 8.—*Series 1. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

follows: The sum of the perpendicular distances from any point within the triangle to the three sides is the same and is equal to the perpendicular distance from an apex to the opposite side. This distance is called 100 or 100 per cent. Each apex represents a grog composition of 100 per cent of the kind of grog designated and the opposite side zero per cent. Hence, to determine the composition, the distance from the given point within the triangle to any side is observed. This is the per cent of material represented by the apex opposite the side chosen. Thus, the grog *J*

is composed of 20 per cent P, 20 per cent A, and 60 per cent M. Each side of the triangle is divided into 10 parts, as indicated by the dashes, but to avoid confusion these are not extended across the diagrams. The curved lines within the triangle are drawn through points representing the grog composition of bodies of equal strength. It is not necessary to consider the clay content of the bodies in the representation, since the per cent of clay is constant.

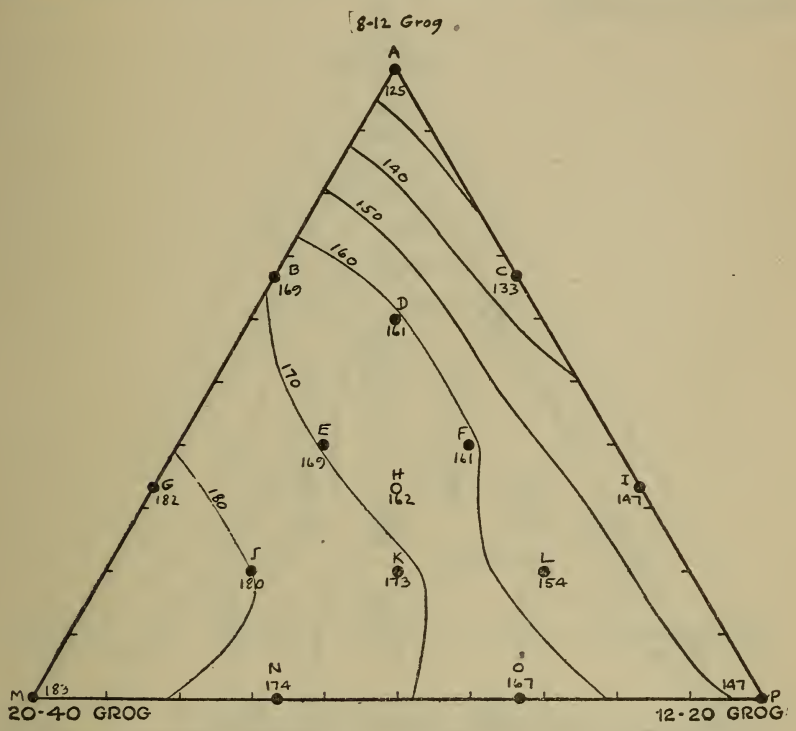

FIG. 9.—*Series 2. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

(*b*) *Analysis of Results by Means of Theory of Voids.*—In glancing over Figs. 8 to 14, one receives the impression of a set of topographical maps, each having its own peculiar arrangement of contour lines. In the present case we are dealing with iso-strength lines and the factors governing the shaping of their courses are not readily discovered. It is noted that the strength of the bodies increased with increase of porosity in series 1, 2, and 3, and with decrease of pore space in series 4. (See Figs. 4, 16, and 17.) The changes in porosity and strength in the first three series were not

coordinate and are explained as follows: Porosity increased because the larger particles were more dense than an equal weight of packed smaller sizes; also, as will be shown later, because the voids were increased by the mixture of sizes. Strength increased because the larger particles gave weaker bodies due to lack of bond and contact between clay and grog. This caused small cracks in drying, which decreased in size with decrease in size of grog. In series 4 no cracks appeared, bond was good, and strength decreased with decrease of porosity.

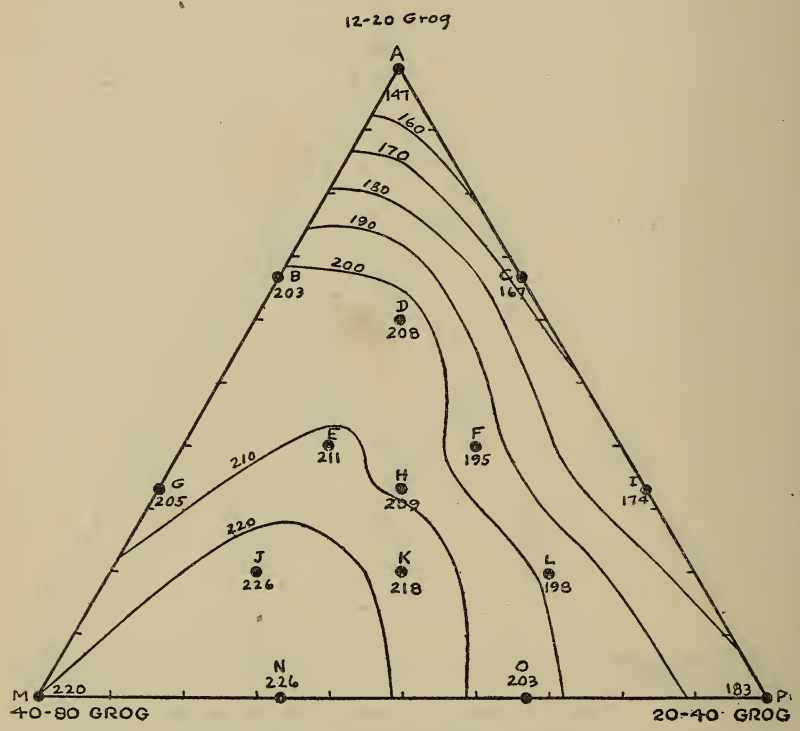

Fig. 10.—*Series 3. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

Fig. 15 shows the relation between the modulus of rupture and the size of grain, expressed as surface factor. If the iso-strength lines in the triaxial diagrams had run straight across the triangles, the relation would have been exact. Since they do not, an explanation of the results must be attempted by means of the theory of voids. It is obvious that mixtures of particles of different sizes give denser bodies than do single sizes, if they are related to each other so that the smaller sizes fit into the voids between the larger sizes. Since clay and grog have approximately the same specific

gravity, they occupy about the same volume per unit volume of briquette body. Hence, the grog particles are in contact with each other in the raw body, except for a comparatively thin layer of clay.

In Table 3 are given the average size of each grog portion and the ratio between the three average sizes in each series·

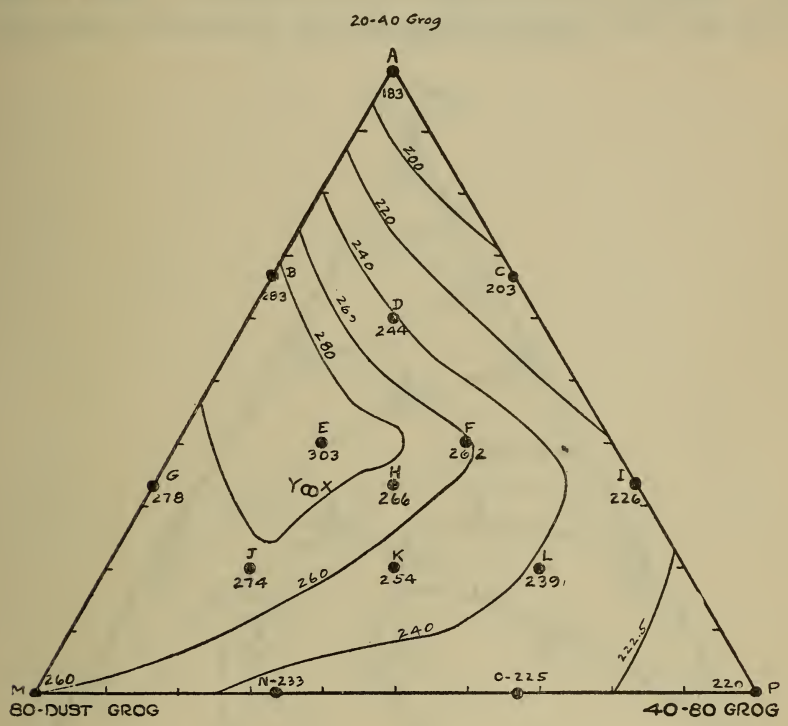

FIG. 11.—*Series 4. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

TABLE 3

Series	Mesh	Average size	Ratio of sizes	Series	Mesh	Average size	Ratio of sizes
		Inch				Inch	
1	4–8	0.1382	1.00	4	20–40	0.0214	1.00
	8–12	.0697	.50		40–80	.0101	.47
	12–20	.0423	.30		80–dust	.0032	.15
2	8–12	.0697	1.00	5–7	4–20	.0834	1.000
	12–20	.0423	.61		20–80	.0157	.188
	20–40	.0214	.31		80–dust	.0032	.038
3	12–20	.0423	1.00	Feret's sands[a]	4–10	.139	1.00
	20–40	.0214	.51		10–30	.050	.36
	40–80	.0101	.24		30–dust	.010	.07

[a] See Fig. 1.

If spheres of equal volume are packed symmetrically in a receptacle, two sizes of voids are formed between them and the three sizes of spheres necessary to form the densest mass have diameters in the ratio 1.00: 0.41 : 0.22. Since the actual shape and size of voids in clay-grog bodies can not be determined, the best means at hand for comparison of the effect of mixing different sized particles must be used. As the above table shows, the ratio of sizes in series 1 and 2 is such that the smaller particles do not fit into the voids, but

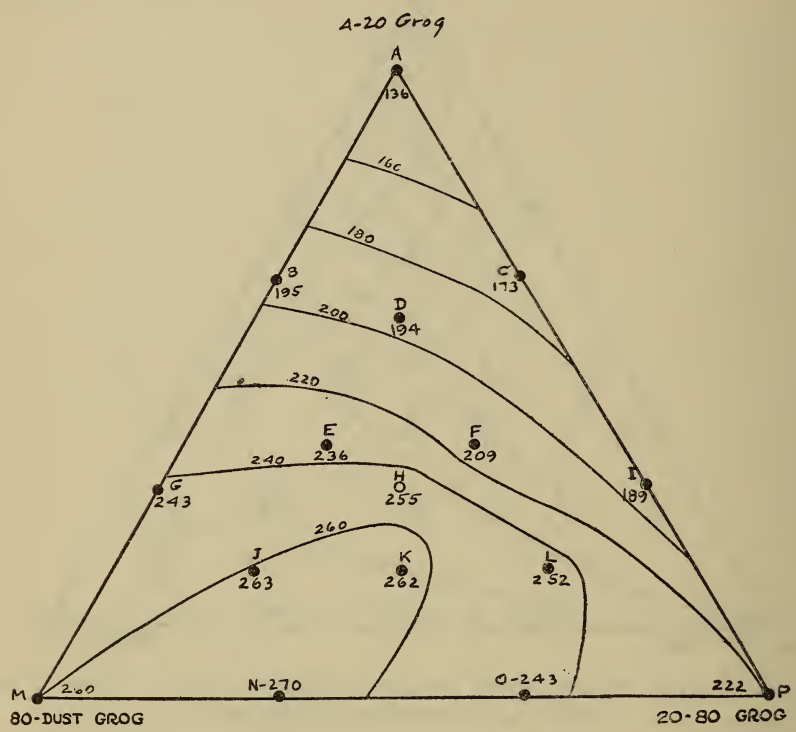

FIG. 12.—*Series 5. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

separate the larger particles. Hence, there are no maximum strength or density areas in these series. In series 3 there is a somewhat better ratio. The 40 to 80 size fits into the voids between either 12 to 20 or 20 to 40 mesh size, giving considerable increase in strength with amounts of 30 per cent and more and a maximum strength area near bodies *J* and *N*.

In series 4 the ratio approaches the theoretical ratio for spheres. The voids in the 20 to 40 material are able to contain 80 to dust material, but most of the 40 to 80 grog is too large, separating the

larger particles causing increase in porosity and decrease in strength.

In series 5 the ratio of sizes shows that the smaller sizes easily fit into the voids between the 4 to 20 size, giving some of the densest bodies obtained. These were not, however, the strongest. Most of the bodies in series 4 (20 to dust grog) were stronger than those in series 5 (4 to dust grog). The large particles in the latter weakened the bond and caused cracks in drying.

FIG. 13.—*Series 6. Relation between grog composition and modulus of rupture for raw bodies. Clay composition: Equal parts fire clay and Georgia kaolin*

The same ratio of grog sizes occurs in the bodies in series 6 and 7 as in series 5. The clay composition, however, is different in each of the three series. In series 6 the theory of the filling of voids applies as well as in series 5. The only difference to be noted is that the addition of Georgia kaolin decreased the strength to about 60 per cent of that of bodies in which the clay was all fire clay.

The results in series 7 were rather surprising when compared with those of series 5. The clays in both were plastic bond clays.

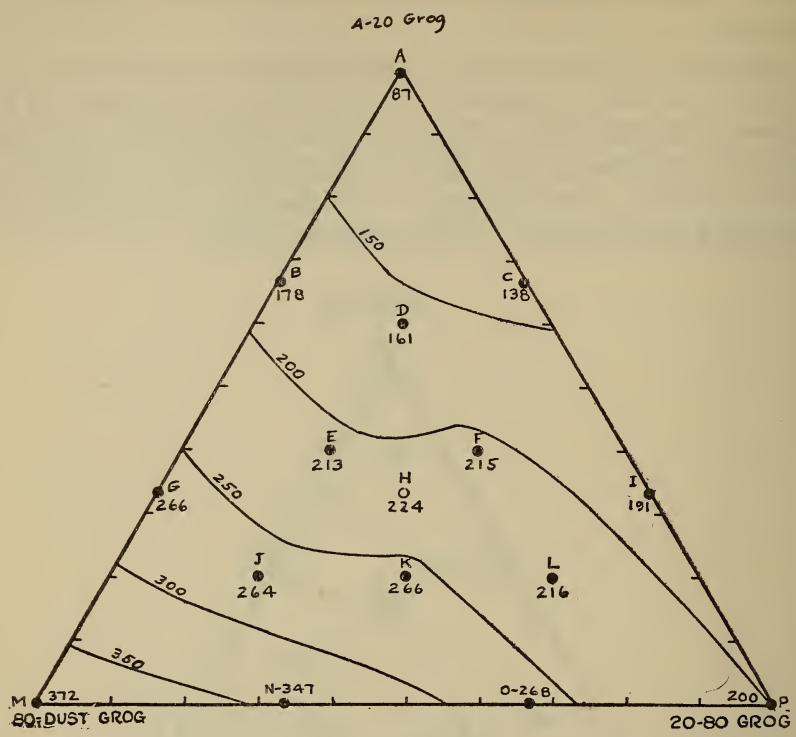

FIG. 14.—*Series 7. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All Illinois Kaolin*

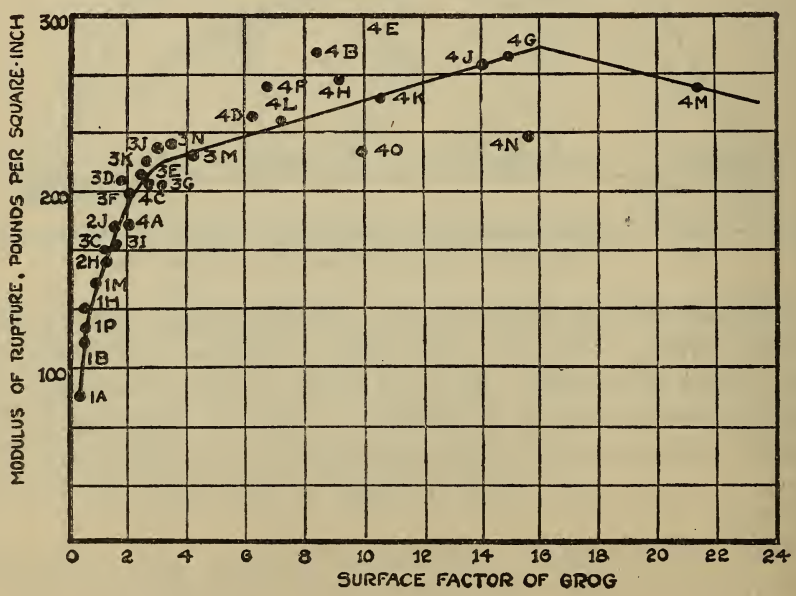

FIG. 15.—*Relation between surface factor and modulus of rupture of raw bodies*

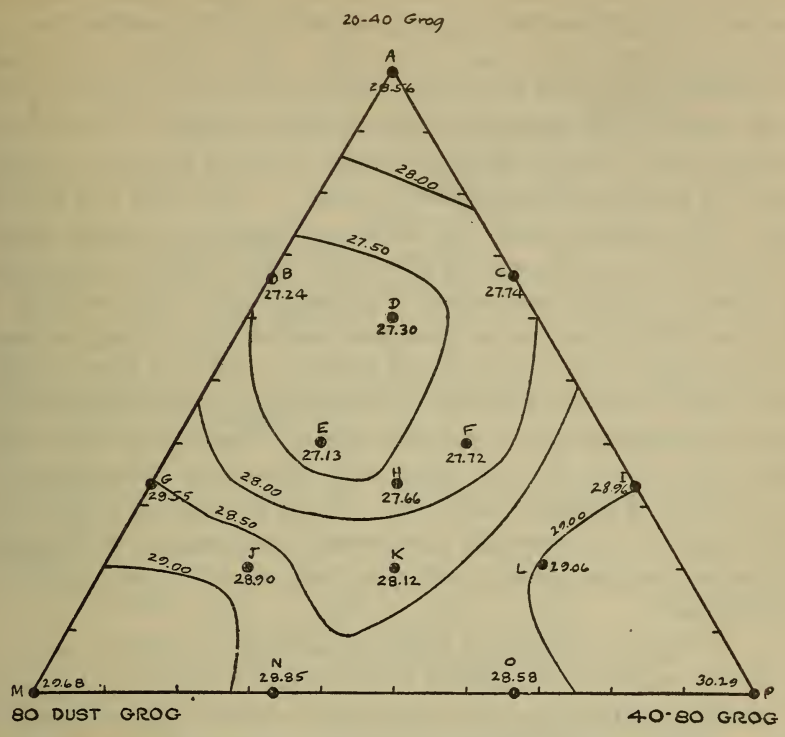

FIG. 16.—*Series 4. Relation between grog composition and porosity of raw bodies*

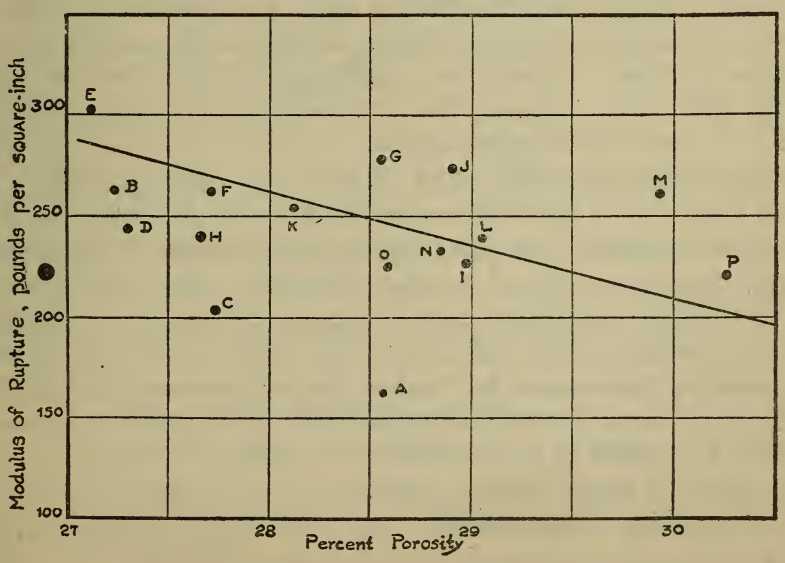

FIG. 17.—*Series 4. Relation between modulus of rupture and porosity of raw bodies*

The Illinois kaolin had less bonding power when coarse grog was used and more when fine grog was employed than had the fire clay. There are at least two reasons for this. The kaolin in the plastic condition is somewhat like putty, while the fire clay has more of a sticky nature and contains more colloidal material. If this were the only factor, all the bodies in series 7 should have been weaker than the corresponding bodies in series 5. But this was not the case. For example, body 7*M* had 1.43 times the strength of 6*M*. The only way to account for this is by assuming that the kaolin contained a certain proportion of grains of such size that they fit into the voids between the finer particles of grog, giving a denser and stronger body. This would indicate that the size of grain of the bond clay as well as the size of grog has considerable influence upon the properties of a fire-clay body. Hence, with the same size of grog, each clay or mixture of clays may be expected to give a body of different structure. Since the size of grain of the clays can not be accurately determined, the strength of clay-grog bodies can not be closely predicted, but must be ascertained by experiment.

(*c*) *Analysis of Results by Means of Granular Analysis Curves.*—While the ratio of sizes affords a convenient means of comparison it should be noted that the average size of each grog portion was used and that each contained particles varying in size from the maximum to the minimum. A more accurate method of study is offered by the granular-analysis curve as illustrated in Fig. 2. The curve of the strongest mixture is different for each group of similar mixtures. It may be a parabola, a straight line, or some other form. In any case, the curve shows accurately what the ratio of sizes shows approximately—that the mixture is so proportioned that the smaller sizes fill the voids most completely.

In Figs. 18 and 19 are shown analysis curves for series 4 and 5. Abscissas represent the percentage passing screens having openings of the sizes indicated by the ordinates. The lines denoted as "Parabola" are Fuller's curves of greatest strength and density. The clay portion of the bodies is not included since it is a constant. In series 4 the curves for bodies having greatest strength lie entirely between the full-line curves; that is, they follow approximately the course of the parabola. In series 5 it is seen that all the curves lie above Fuller's parabola and that strength decreases as the parabola is approached. For bodies which contain all the sizes, the maximum-strength curve is approximately that designated "maximum." With substitution of the proper values of

strength, Fig. 19 applies also to series 6 and likewise to series 7, except for the maximum curve. Thus, it is seen that the general

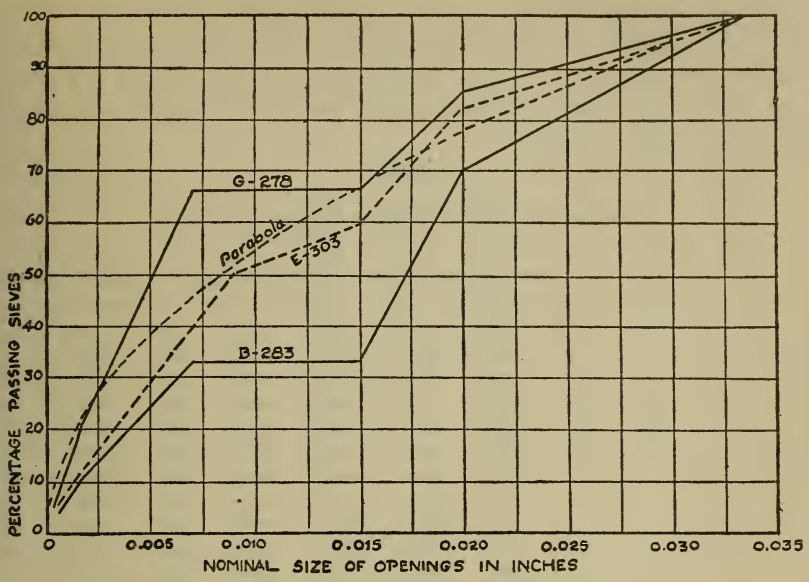

FIG. 18.—*Series 4. Mechanical analysis curves of grog*

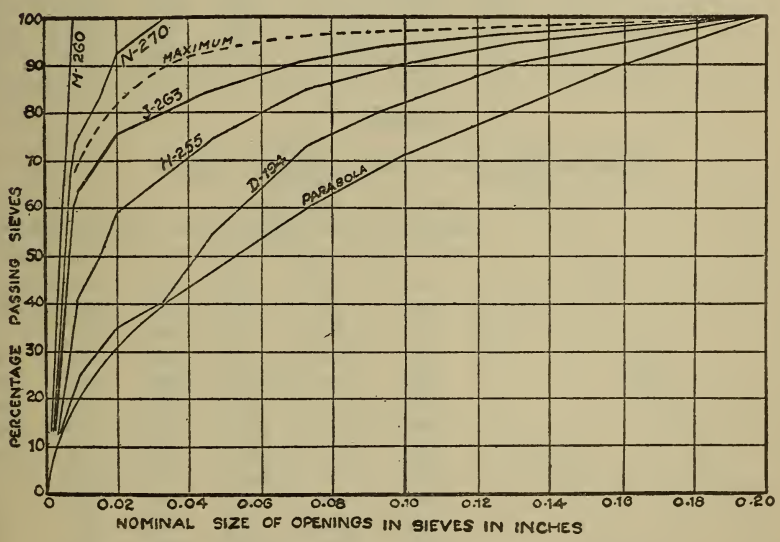

FIG. 19.—*Series 5. Mechanical analysis curves of grog*

principle of Fuller's law holds, although the law is not directly applicable in all cases.

2. RESULTS OF TESTS UPON BODIES IN THE BURNED STATE

(*a*) *Strength and Porosity.*—Bodies were burned to three temperatures, corresponding to heat treatments of cones 10, 12, and 14. Table 4 gives the moduli of rupture for cone 10 bodies, Table 5 shows strength, and Table 6 porosity of cone 12 bodies. Figs. 20 to 25 show the relation between grog composition and modulus of rupture of cone 14 bodies.

TABLE 4

Modulus of Rupture of Bodies Burned to Cone 10

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7
A	390	698	919	1381	779	740	453
B	553	1141	1330	2294	1334	1232	1350
C	668	845	1014	1538	1061	1108	827
D	682	969	1394	1986	1302	1184	1121
E	780	1105	1491	2387	1687	1600	1658
F	563	923	1498	2251	1713	1619	1424
G	900	1328	1731	2618	1992	1835	1900
H	779	935	1673	2389	2011	1780	1869
I	731	941	1337	1555	1404	1384	1222
J	845	1298	1659	2160	2061	1972	2090
K	893	1205	1681	2011	2101	1904	1888
L	794	1037	1470	1875	1825	1737	1589
M	1029	1381	1978	2479	2479	2410	3012
N	1037	1188	1981	2368	2625	2484	2474
O	953	1100	1529	1976	2248	1973	1954
P	698	919	1381	1978	1700	1723	1429

TABLE 5

Modulus of Rupture of Bodies Burned to Cone 12

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
A	529	716	925	1467	749	757
B	687	1000	1428	2400	1548	1395
C	549	742	1110	1628	1247	1039
D	589	935	1353	2074	1624	1402
E	660	1167	1623	2518	1954	1975
F	659	966	1439	2300	1861	1679
G	766	1218	1763	2815	2296	1919
H	749	1158	1859	2400	2158	2047
I	618	923	1300	1915	1656	1552
J	784	1219	1953	2683	2617	2512
K	684	1210	1823	2417	2632	2149
L	705	1100	1496	2208	2135	1847
M	925	1467	1866	3007	3007	2619
N	923	1300	1915	2808	3198	2859
O	742	1110	1628	2268	2744	2372
P	716	925	1467	1866	2200	1815

TABLE 6

Porosity of Bodies Burned to Cone 12

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7
A	19.8	22.8	24.0	25.1	22.5	28.7	24.6
B	21.7	22.5	24.3	22.8	22.0	26.3	24.0
C	20.5	23.0	25.0	25.2	22.7	27.5	25.9
D	21.5	22.8	24.1	23.1	21.0	26.8	23.8
E	22.3	23.5	24.6	22.1	21.9	26.8	25.0
F	21.8	24.2	24.3	23.9	22.7	26.9	25.3
G	22.9	23.6	24.5	22.5	21.9	26.3	24.5
H	22.5	24.4	24.3	23.6	20.3	26.3	24.5
I	21.4	23.6	25.1	26.1	23.6	27.3	26.1
J	23.6	24.5	24.6	23.2	21.0	26.4	23.2
K	22.3	24.7	24.7	24.0	21.6	25.8	23.6
L	22.6	23.9	25.1	24.3	21.4	27.6	26.5
M	24.0	25.1	26.5	24.7	24.7	26.5	24.0
N	23.6	25.0	26.1	24.0	22.6	26.9	25.1
O	23.0	25.0	25.2	23.4	22.6	26.2	27.3
P	22.8	24.0	25.1	26.5	25.7	29.1	29.5

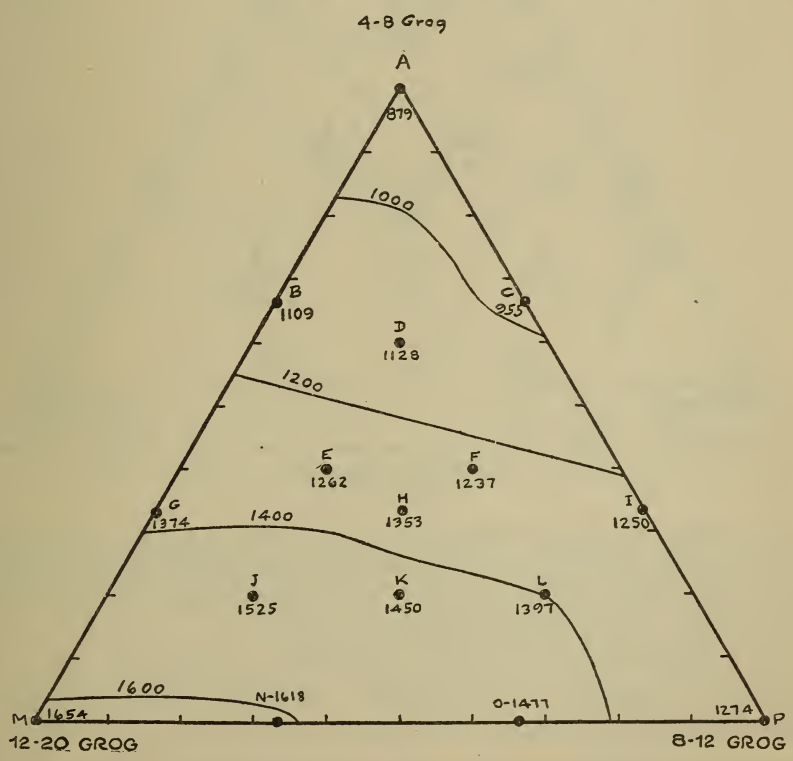

FIG. 20.—*Series 1. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

In series 1 to 4 the modulus of rupture at cone 12 bears an approximate relation to porosity. The strength-porosity curve (Fig. 26) consists of two parts. From body 1*A* (4 to 8 grog) to bodies in series 3 (12 to 80 grog) strength increased with increase of porosity, due to small cracks which developed in drying and did not heal in burning. In series 4 (20 to dust grog) and part of series 3 strength decreased with increase of porosity, the degree of vitrifi-

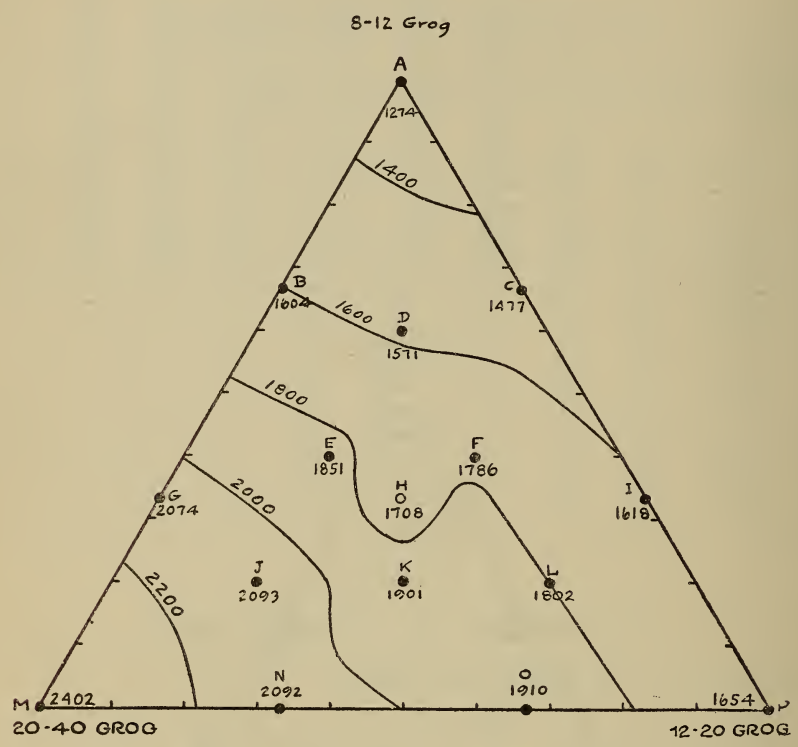

FIG. 21.—*Series 2. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

cation being the governing factor. In series 5 (4 to dust grog) there was no relation between porosity and modulus of rupture. Hence, for bodies containing grog of different sizes, porosity may give entirely wrong indications of strength.

The surface factor, however, does afford an accurate means of judging the strength of such bodies. In Figs. 27 and 28 surface factor of the grog portion of the bodies is plotted against modulus of rupture. The curves are straight lines except that some are of

parabolic form in the lower part; that is, for larger grog sizes. The relation holds for all the series at all three heat treatments. It is more exact in series 1 to 4 than in series 5 to 7, because the latter contain comparatively large particles which are not dissolved by the clay to anywhere near the same extent as are the small particles.

(*b*) *Quenching Tests from 600° C.*—The results of these tests are presented in Table 7 and Fig. 29. Bodies retaining the greatest

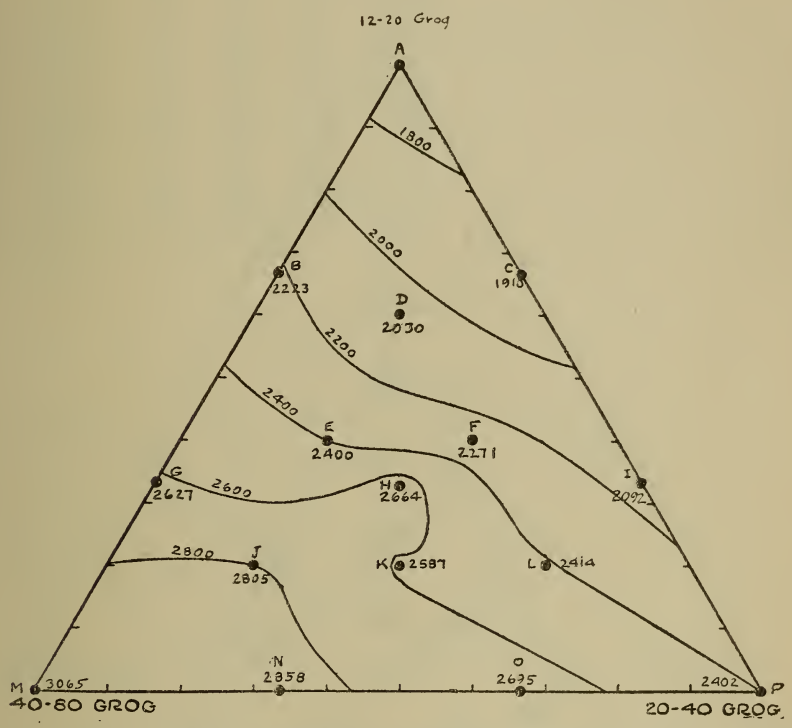

FIG. 22.—*Series 3. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

percentage of strength were those in series 2, these, of course, overlapping certain portions of series 1 and 3. Bodies containing 8 to 40 mesh grog in the proper proportions withstood the treatment best, having values from 50 to 60 per cent strength retained. The bodies in series 5 and 6 nearly all retained a smaller percentage of strength than those in series 2, on account of the fine grog in the former.

TABLE 7

Per Cent of Strength Retained by Bodies after Quenching from 600° C Five Times

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
A	34.2	46.3	50.0	53.4	46.6	43.4
B	48.5	54.8	42.5	39.6	40.8	48.2
C	38.8	50.4	50.6	48.4	51.7	50.7
D	40.6	51.2	48.7	36.4	47.9	51.6
E	43.9	47.3	45.9	37.8	42.4	43.4
F	48.5	49.5	47.0	36.9	43.0	48.1
G	46.5	49.2	39.7	32.4	30.5	32.7
H	46.6	54.5	41.4	36.8	49.2	40.4
I	41.4	50.0	48.0	41.8	49.4	57.1
J	50.1	57.6	38.0	37.5	27.5	27.5
K	55.0	53.2	42.5	37.2	35.2	35.0
L	58.3	50.0	46.9	36.6	46.4	50.2
M	50.0	53.4	40.0	14.3	14.3	18.7
N	50.2	48.0	41.8	31.4	18.5	18.4
O	50.4	50.6	48.4	37.8	34.0	31.0
P	46.3	50.0	53.4	40.0	55.3	48.0

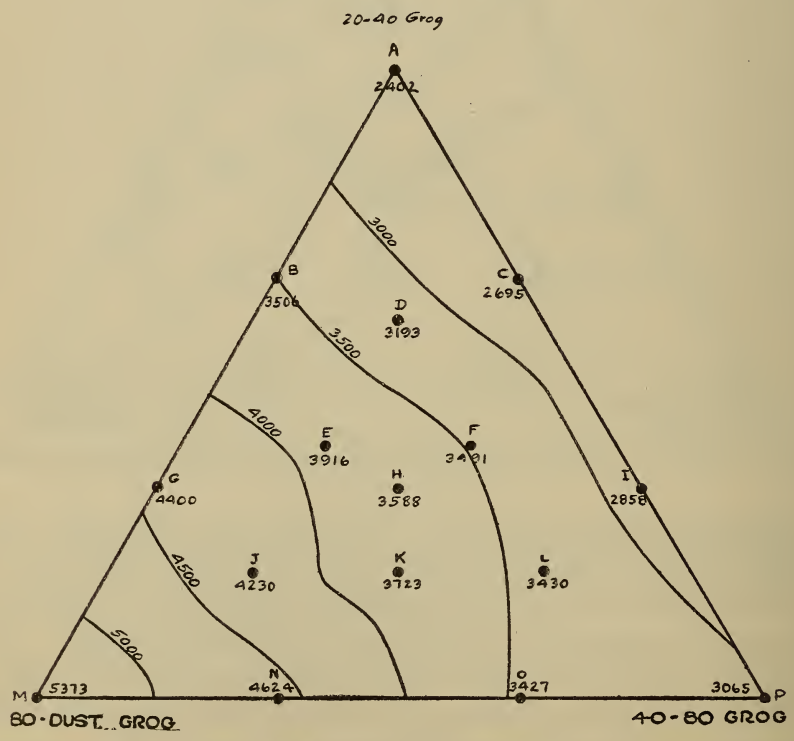

FIG. 23.—*Series 4. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

(*c*) *Quenching Tests from 1000° C.*—The results from these tests are given in Table 8 and Fig. 29. The most resistant bodies were found in series 1 and 2 (4 to 40 mesh grog). In Fig. 29 surface factor is plotted against results of quenching tests. The results for 600° C agreed fairly well with those for 1000° C. Since this is true, it might be possible to replace the 1000° test by the more accurate 600° test. In general, increase of surface factor caused

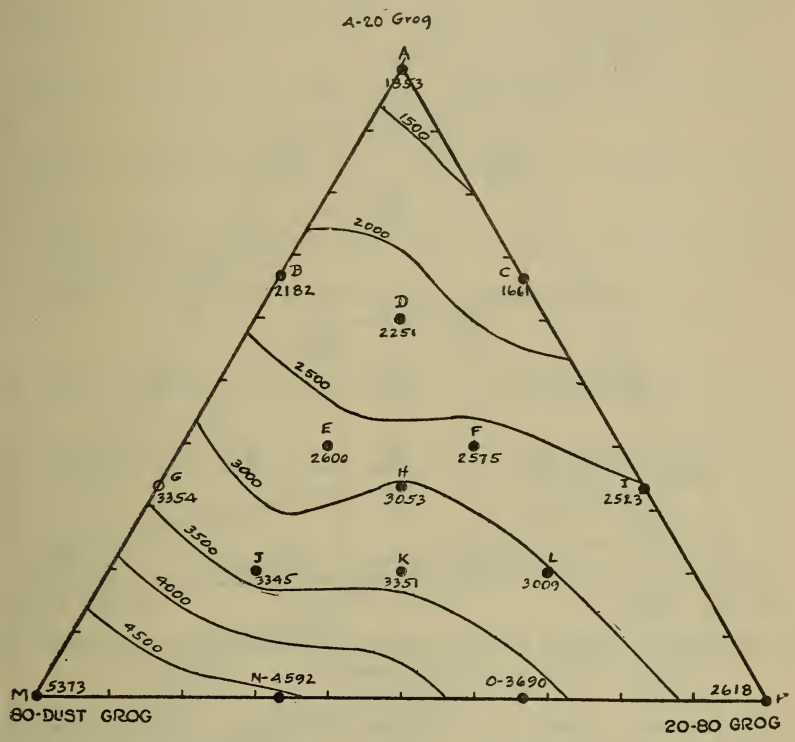

FIG. 24.—*Series 5. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

decrease in resistance to sudden heating and cooling. The portion of the curve from 1*A* to 1*D*, etc., indicates that the largest size grog was too large for the briquettes used, causing spalling and destruction of the body. Four standard-size fire brick containing small-size grog (through 20 mesh or finer) were heated with the briquettes in these tests. The brick cracked in two on the average at the seventh treatment. Two fire brick containing large-size grog (about ¼ inch) cracked or spalled in two on the average upon

the twenty-fifth treatment. Hence, standard-size brick of the compositions used in this investigation would withstand, on account of their dimensions, two or three times the number of treatments undergone by the briquettes before breaking in two.

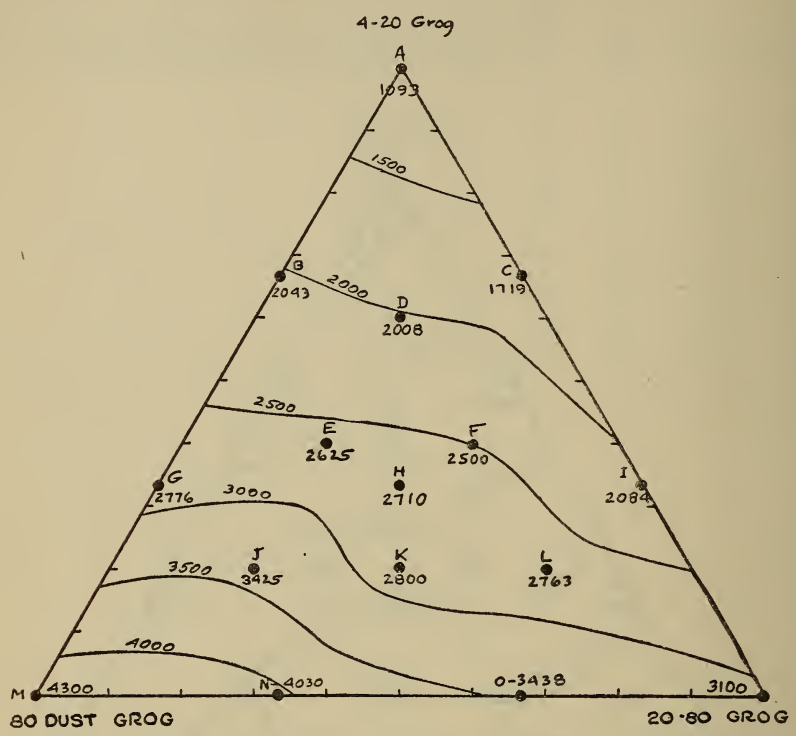

FIG. 25.—*Series 6. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

(*d*) *Volume Shrinkage.*—Volume shrinkage of the bodies in burning to cone 12 is given in Table 9. Comparison of the values in Tables 6 and 9 shows that increase in shrinkage corresponds to decrease of porosity. Neither of these properties, however, corresponds to changes in strength. It is noted that shrinkage in series 7 was much greater than in any other series, due to the nature of the Illinois kaolin.

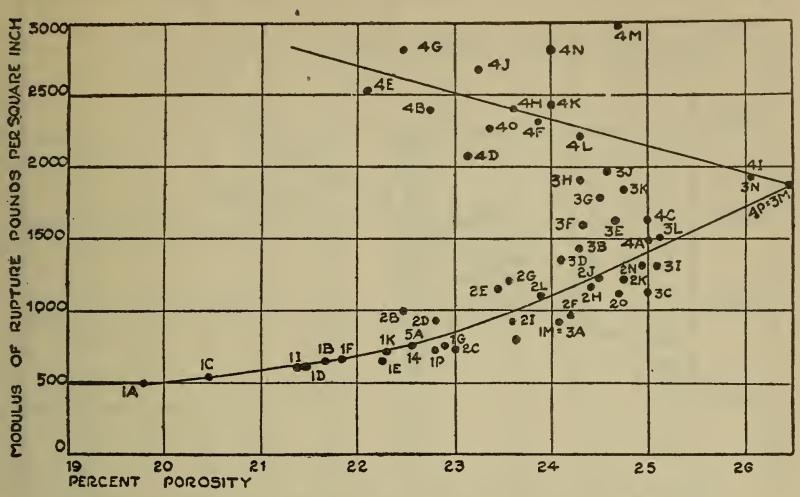

FIG. 26.—*Relation between porosity and modulus of rupture at cone 12*

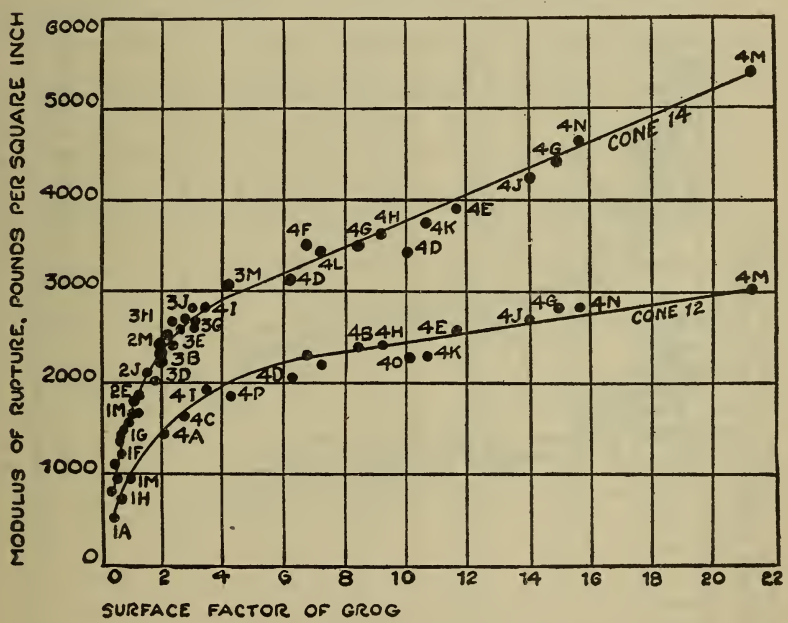

FIG. 27.—*Relation between surface factor and modulus of rupture*

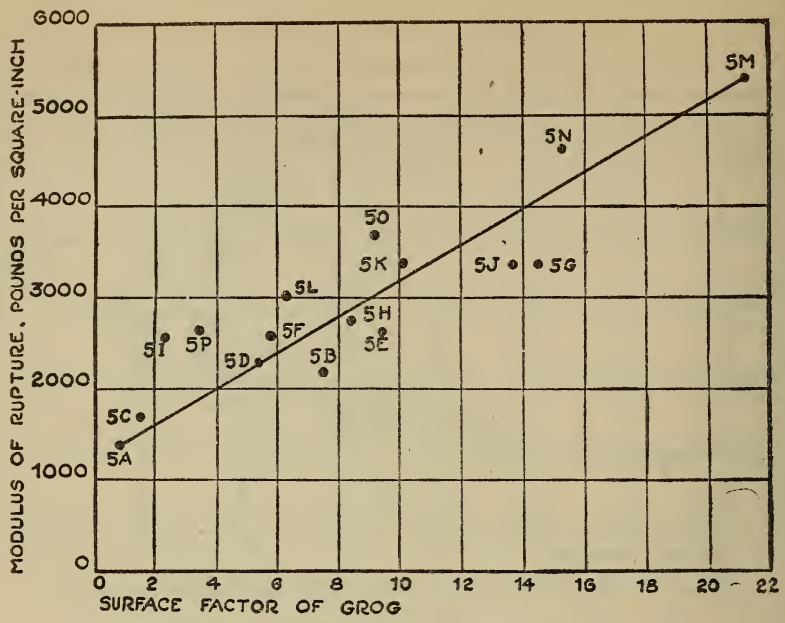

FIG. 28.—*Relation between surface factor and modulus of rupture*

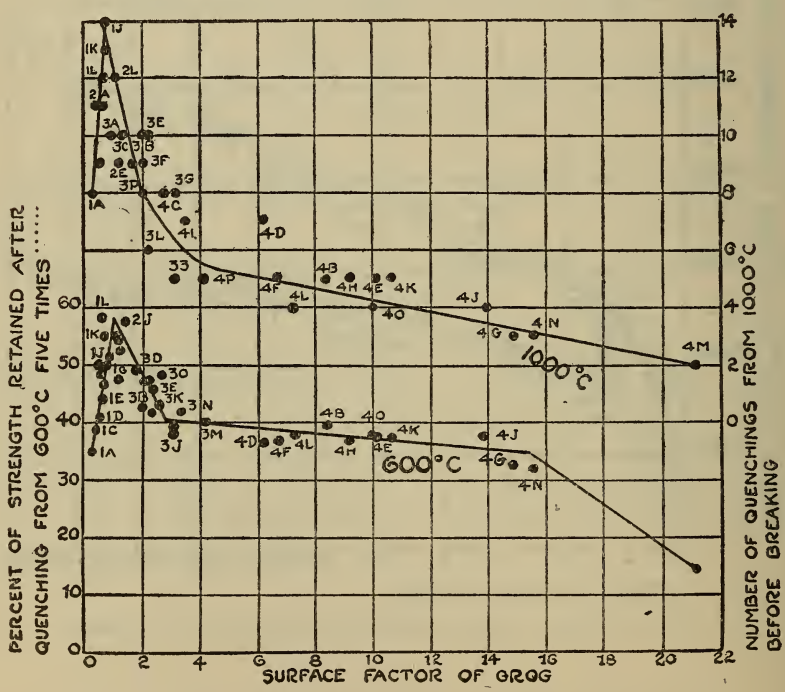

FIG. 29.—*Relation between surface factor and results of quenching tests*

TABLE 8

Number of Quenching Treatments Withstood from Temperature of 1000° C

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
A	8	11	10	8	12	3
B	9	10	10	5	4	5
C	11	10	10	8	5	8
D	12	10	9	7	3	7
E	12	9	10	5	3	6
F	12	11	9	5	3	6
G	10	8	8	3	2	2
H	12	11	10	5	2	3
I	11	10	9	7	3	5
J	14	9	4	4	2	1
K	13	10	4	5	2	2
L	12	12	6	4	3	5
M	10	8	5	2	2	1
N	10	9	7	3	2	3
O	10	10	8	4	2	3
P	11	10	8	5	3	4

TABLE 9

Volume Shrinkage of Bodies, in Per Cent of Burned Volume, Burned to Cone 12

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7
A	8.55	8.03	7.53	7.75	6.96	9.15	9.40
B	5.85	6.57	6.41	9.24	7.28	8.28	13.51
C	9.06	7.38	6.52	7.40	5.64	8.47	14.66
D	7.48	7.70	6.53	8.24	7.50	8.72	13.84
E	7.19	7.45	6.66	10.67	8.08	8.75	13.58
F	7.85	7.46	7.45	7.57	6.80	7.67	13.72
G	7.00	7.37	7.93	9.72	8.68	9.00	13.30
H	6.96	7.21	7.36	8.40	9.23	9.86	12.49
I	6.90	7.50	6.45	6.81	6.52	9.35	12.20
J	4.81	6.79	7.02	8.27	10.35	9.76	14.18
K	7.21	7.09	7.63	9.57	8.41	10.66	13.68
L	6.53	6.34	7.93	8.35	9.86	10.33	12.85
M	7.53	7.75	8.15	9.94	9.94	9.74	14.14
N	7.50	7.10	8.40	9.40	9.68	9.75	13.42
O	7.38	5.89	7.50	9.78	8.95	9.61	12.98
P	8.03	7.53	7.75	8.15	7.35	8.27	11.78

TABLE 10

Surface Factor [a] of Grog Portions of Bodies

	Series 1	Series 2	Series 3	Series 4	Series 5–7
A	0.308	0.582	0.956	1.950	0.613
B	.525	1.038	2.037	8.409	7.530
C	.400	.707	1.286	2.703	1.430
D	.552	.930	1.805	6.241	5.254
E	.622	1.204	2.455	10.164	9.404
F	.547	1.000	2.000	6.729	5.744
G	.741	1.494	3.126	14.882	14.448
H	.616	1.163	2.371	9.169	8.348
I	.491	.832	1.615	3.443	2.248
J	.752	1.478	3.097	13.939	13.555
K	.677	1.278	2.654	10.610	9.895
L	.602	1.080	2.200	7.172	6.236
M	.956	1.950	4.211	21.365	21.365
N	.832	1.615	3.456	15.631	15.266
O	.707	1.286	2.702	9.991	9.166
P	.582	.956	1.947	4.190	3.066

[a] Calculated in the usual manner, the diameters of the particles being expressed in millimeters.

VI. SUMMARY OF RESULTS

The control of the strength of raw fire-clay bodies is a difficult matter into which enter a number of factors. Those which are directly connected with the size of grog are size of the body, cracks formed in drying, density or porosity, and size of grain of the clay.

If the grog is too large for the size of body used, the conditions of bond are different than for smaller grog. Small cracks may or may not form in drying. Hence, it is possible that the curve of Fig. 4 would be much different for test pieces of larger dimensions. The general rule in ceramic bodies is that strength increases with decrease of porosity. This factor may be overruled by others, as the results in Fig. 4 show. In series 4, however, the rule holds. As shown in connection with series 5 and 7 the size of grain of the bond clay also affects the strength of the body. In regard to the grog, aside from other considerations, the following condition is necessary for highest strength. The mixture of sizes must be such that the smaller particles fill the voids between the larger, giving maximum density. The proper proportions may be predicted qualitatively from the ratio of sizes, but can be determined accurately only by experiment.

The strongest raw bodies were those in series 4 and 7. In series 4 these had the following limits of grog composition: 25 to 66⅔ per cent, 20 to 40 grog; 0 to 25 per cent, 40 to 80 grog; and 33⅓

to 66⅔ per cent, 80 to dust grog. In series 7 the strongest bodies were those containing the greatest percentage of 80 to dust grog.

The control of strength in the burned state proved to be not at all difficult. For all bodies used the modulus of rupture was found to increase with increase of surface factor. The relation was represented by means of straight lines except that the lower portions of some of the curves representing large-sized grog were of parabolic form. The rate of increase of strength increased with the temperature of burning, due to the more rapid rate of solution of the finer particles at the higher temperatures. The porosity at cone 12 varied much the same as in the raw bodies and had little relation to strength. The strongest bodies were those in series 4 (20 to dust grog). No relation was found between strength in the raw state and in the burned state.

In the quenching tests from 600° C and 1000° C mixtures of the larger sizes of grog gave the more resistant bodies.

VII. APPLICATION OF RESULTS

Although the laboratory investigation has not been supplemented by practical work, it may be of value to indicate a few methods of application. Grog for glass pots and similar bodies may contain too much fine or intermediate-sized grog, causing low strength and cracking in drying. The composition of 20-mesh grog may be corrected by reference to Fig. 11. The best bodies have compositions within the maximum strength area described above. These had moduli of rupture of from 275 to 300 pounds per square inch in the raw state and from 3500 to 4400 pounds per square inch in the burned state. Point *X* in Fig. 11 represents the composition shown by the parabola of Fig. 18. Point *Y* represents closely the composition of grog furnished by the Harbison-Walker Refractories Co., of Pittsburgh, Pa., for the investigation of Bleininger and Schurecht on European Plastic Fire Clays.[7] This shows that grog may be ground to give the proportions for maximum strength. Where screening into separate sizes and recombining is not economical, this may be accomplished by control of the conditions of grinding, as time, size of openings in screen plates, pressure, etc.

The question of sagger loss is a serious one in many plants. A review of German, French, and American practice discloses many different methods of sagger manufacture. Composition is

[7] B. S. Technologic Paper No. 79, p. 19.

much varied. The clays used are of all grades from kaolins to shales and possess all degrees of plasticity and refractoriness, necessitating the use of various percentages of grog. The latter varies in composition from the best flint fire clay to used bats of various degrees of disintegration.

In American practice grog for saggers is used all through 3 to 6 mesh screens, while German and French manufacturers separate it into two or three sizes, classified roughly as fine, medium, and coarse. There is a wide variation in the proportions of sizes used, there being apparently no fundamental basis of reason for compounding the mixtures. In general, the larger the sagger the larger are the sizes of grog used. In some instances additions of sawdust, coal powder, quartz sand, alumina, or other materials are added to the mixture to increase porosity or refractoriness. Many ingenious methods have been devised for shaping, molding, and reinforcing saggers. Machine-made saggers are found to be more satisfactory than handmade. The temperature of burning varies much and has considerable influence upon the length of life of the sagger.

In attempting to apply the results of this investigation to saggers the size of grog must be assumed to be the governing factor. Otherwise the application might go far astray. Other factors having been eliminated the grog compositions given in Table 11 seem best suited for saggers having walls and bottoms 1 inch in thickness.

TABLE 11

		Per cent of composition passing sieves					Per cent strength retained, 600° C test	Quenching treatments withstood, 1000° C test	Modulus of rupture, pounds per square inch	
		4–8 mesh	8–12 mesh	12–20 mesh	20–40 mesh	40–80 mesh			Raw state	Burned state
Group I	1K	20	40	40	.....	.....	55.0	13	142	1450
	1L	20	60	20	.....	.....	58.3	12	136	1525
	2J	.....	20	20	60	.....	57.6	9	180	2093
	2H	.....	33⅓	33⅓	33⅓	.....	54.5	11	162	1901
Group II	3A	.....	.....	100	.....	.....	50.0	10	147	1654
	3C	.....	.....	66⅔	33⅓	.....	50.6	10	167	1910
	3D	.....	.....	60	20	20	48.7	9	208	2030
	3F	.....	.....	40	40	20	47.0	9	195	2271
	3I	.....	.....	33⅓	66⅔	.....	48.0	9	174	2092
	3L	.....	.....	20	60	20	46.9	6	198	2414
	3O	.....	.....	.....	66⅔	33⅓	48.4	8	203	2695
	3P	.....	.....	.....	100	.....	53.4	8	183	2402

Group I is recommended where resistance to repeated heating and cooling is desired more than strength. In Group II resistance to repeated heating is sacrificed to obtain bodies of greater strength. The results show that both very large and very fine grog are undesirable in sagger bodies of the compositions used in this investigation.

The results throw some light upon the question of the bonding power of plastic clays. The strength of clay-grog bodies in the raw state is a measure of bonding power. Since size of grog has great effect upon strength, size of grain of the clay must exert considerable influence upon this property. The size of grain of bond clays can not at present be measured accurately. Any means for determination or indirect estimation of this property, such as viscosity of the clay slip, would be of great help in working out this problem.

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