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INVESTIGATION OF ENDURANCE OF BOND STRENGTH OF VARIOUS CLAYS IN MOLDING SAND

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CONTENTS

4   CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

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INVESTIGATION OF ENDURANCE OF BOND STRENGTH OF VARIOUS CLAYS IN MOLDING SANDS

I. Introduction

1. *Introductory.*—Molding sands consist of clay, silica sand, and water. The clay acts as a bond to hold the grains of sand together, so that the impression of the pattern in the molding sand will maintain its form or shape until the molten metal poured into the mold has solidified. The bond strength, or cohesiveness, of the molding sand depends largely upon the quantity and type of clay present.

In the past few years producers of clays have been marketing clays known as bonding or rebonding clays. These clays are used to make artificial molding sands, or to replace the original clay in used sands, whose bond strength has been destroyed by the action of the molten metal.

The clays tested in this investigation are listed in Table 1, which also gives the sources, and the letters assigned to them in this work. All clays were bought in the open market.

2. *Acknowledgments.*—This investigation has been part of the work of the Engineering Experiment Station of the University of Illinois of which Dean M. S. Ketchum is director, and of the Department of Mechanical Engineering of which Prof. A. C. Willard is head.

Acknowledgment is made to Dr. A. I. Andrews of the Ceramics Department of the University for furnishing information as to fusion points on six of the clays tested.

II. Objects of Investigation

3. *Objects.*—This investigation was conducted
  (a) to determine physical and chemical properties of clays tested;
  (b) to compare the various clays for endurance of bond strength when used as bonds in molding sands under casting conditions;
  (c) to determine the thermal conductivity of molding sands and the effect of heat on clays and molding sands;
  (d) to determine the effect of repeated heatings on the permeability of molding sands.

7

TABLE 1
LIST OF CLAYS TESTED

Clay	Class of Clay	Source	Clay	Class of Clay	Source
A..............	Fire Clay	Illinois	F............	Ball Clay	Florida
B..............	Shale	Illinois	G............	Fire Clay	Missouri
C..............	Fire Clay	Illinois	H............	Unknown	Unknown
D..............	Ball Clay	Tennessee	I............	Unknown	Arkansas
E............	Ball Clay	Kentucky			

III. APPARATUS

4. *Apparatus Used in This Investigation.*—A Ro-tap machine, and a set of U. S. Standard sieves, 40, 70, 100, 140, 200, 270 and pan, were used for all fineness determinations. Sedimentation rates were determined by means of a glass tube, $\frac{3}{8}$ in. in diameter and 32 in. long, stopped at one end. Ignition losses were determined in an electric muffle furnace. The temperatures in this furnace, and wherever else possible, were read with a base metal thermocouple and galvanometer.

Bond strength, permeability, and moisture tests on the molding sands were made by means of apparatus approved by the American Foundrymen's Association.* Temperatures on molten metal were too high to permit the use of a thermocouple and a radiation pyrometer was used for these readings.

The sands were stored in wide mouth glass bottles having paraffin covered corks. Two rammers were used in making the molds, one a regular floor rammer having a three-inch butt diameter, and the other a wooden rammer $\frac{5}{8}$ in. in diameter. The flasks were 12 in. sections of boiler tubing, having an inside diameter of 3 $\frac{1}{8}$ in. Two patterns were used, as are shown in Fig. 1.

Sedimentation determinations, after ignition of clays, were made in a glass tube 12 in. long and $\frac{3}{8}$ in. in inside diameter with a combination wooden plug and pedestal on one end and a meter scale behind the tube. Figure 2 illustrates this piece of apparatus. Heat-effect tests on molding sands were made in a muffle furnace with porcelain containers for the sands. Figure 3 illustrates a transite† container for small molds, containing a thermocouple, which was inserted in a muffle furnace.

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*Standard and Tentatively Adopted Methods of Testing and Grading Foundry Sands, A.F.A., 1928.
†Non-conductive hard asbestos material.

First Pattern
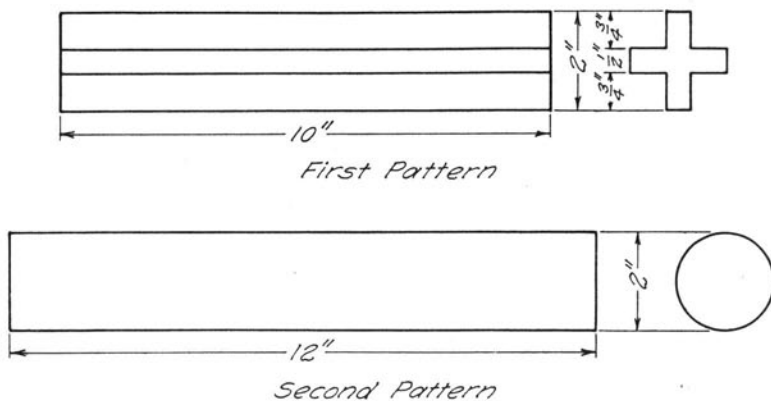
Second Pattern

FIG. 1. FIRST AND SECOND PATTERN

IV. METHODS

5. *Methods for Determining Physical and Chemical Properties of Clays.*—Fineness tests on clays were made by placing 100 grams of dried clay in the Ro-tap machine and running it for 30 minutes. The weight of clay retained on each sieve was then determined.

This method of testing for fineness was used for determining the fineness of the clays as it is commonly used in foundry sand testing laboratories.

Ignition losses were determined by heating one gram of dry clay for 30 minutes at a temperature of 705 deg. C. (1301 deg. F.). Thirty minutes was arbitrarily chosen because it was thought that clay in a molding sand would not be subjected to heat for a greater length of time during the life of the sand.

These clays were then cooled in a dessicator and reweighed. The loss in weight was taken as the ignition loss for the clay. Chemical analyses of the clays were made by accepted methods* for silicate minerals.

Half-gram samples of the various clays were boiled with 10 c.c. portions of distilled water for 10 minutes. Four drops of phenolphthalin indicator solution were added to each sample and these samples were then titrated with a one-hundredth normal sodium hydroxide or hydrochloric acid solution, as the case required, to establish neutrality. The volume of reagent in cubic centimeters required to

*Scott, "Standard Methods of Chemical Analysis," and Mahin, "Quantitative Analysis," 3rd Edition.
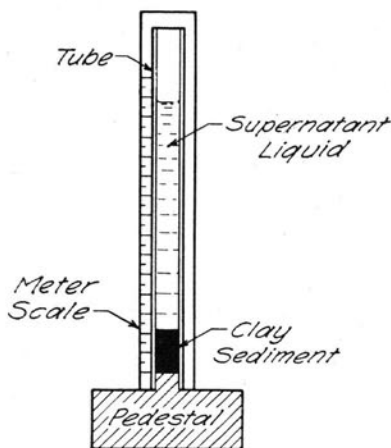
FIG. 2. SHORT SEDIMENTATION TUBE

neutralize indicated the apparent degree of alkalinity or acidity of the given clay.

Fusion points on these clays were determined by comparison with pyrometric cones, and were furnished by the Ceramics Dept.

Colloidal condition of the clays was determined by mixing 10 grams of dry clay with 50 c.c. of distilled water, and placing this mixture in a 32-in. sedimentation tube. The time required for the clearing of the supernatant liquid was taken as a measure of the colloidal condition of the clay.

6. *Methods Used in Endurance Tests of Bond Strength of Sands.*— For the first five sets of castings* a pattern similar to the upper one shown in Fig. 1 was used, and for the last five sets a pattern similar to the lower one. The first of these patterns gave a large surface with a comparatively small volume. The surface area was 64 square inches, with the sand extending 8 inches up on the pattern when rammed. The volume of the casting in this case was 14 cubic inches. The round pattern had a surface area of only 50.3 square inches and a volume of 25.1 cubic inches with the same depth of sand.

There were two reasons for changing the style of pattern at the end of the fifth set of castings. One reason was to compare the bond strength losses caused by a large-volume, small-surface casting with

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*A set of castings means one casting in each sand.
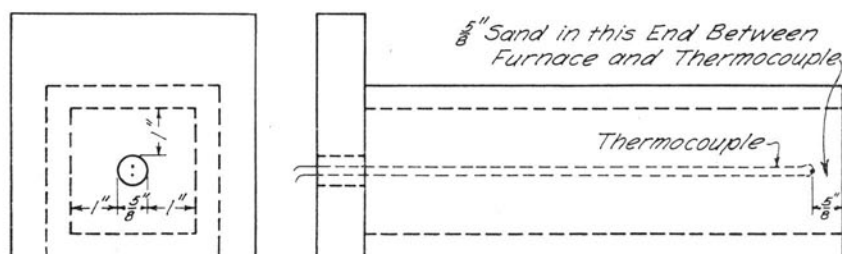
FIG. 3. TRANSITE FLASK FOR THERMOCOUPLE

those caused by a small-volume, large-surface one. The reason for changing from a sharp-cornered to a round pattern was to secure a pattern which could be more easily drawn from the weakened sands without breaking up the molds.

7. *Methods of Preparing Artificial Molding Sand Samples.*—Washed silica sand was used as a base for the samples, and the fineness of this sand was determined. The results are given in Table 2. The analysis of this sand was SiO_2, 98.75 per cent, Fe_2O_3, 0.05 per cent, and merely traces of Al_2O_3, MgO, CaO, and alkalies.

The clays used were designated by letters; these letters were also used to designate the sand samples prepared from the respective clays.

Five hundred grams of a given dried clay were weighed out, thoroughly mixed with 200 grams of silica sand, and sufficient distilled water was added to give a moisture content of seven per cent in the sample. These samples were then assigned the same letters as the clays used for bond in making them. Nine sand samples thus were prepared, one for each clay.

The molding sands were thoroughly mixed and placed in the humidors, and then tempered for 30 days, being mixed by hand five times during this period. At the end of this period the samples were tested for moisture and adjusted to 7 per cent, plus or minus 0.2 per cent. Tempering was then continued for 24 hours longer.

8. *Details of Test.*—The prepared sand was tested for bond strength by means of the Bar Strength Test (Doty Method) apparatus.* Permeability was determined by the A.F.A. standard permeability machine* and moisture by drying 100 grams of sand in an

*Standard and Tentatively Adopted Methods of Testing and Grading Foundry Sands, A.F.A., 1928, pp. 6 and 46.

TABLE 2
FINENESS OF SILICA SAND BASE

Sieve Number	Grams Remaining on Sieve	Sieve Number	Grams Remaining on Sieve
40	5.2	200	2.1
70	63.9	270	0.2
100	21.1	Pan	0.2
140	7.2		

electric oven for one hour at a temperature of 105 deg. C. and noting the loss in weight. Then one of the flasks was set upright on a galvanized iron plate, and some of sample A placed in it, and rammed with a hand rammer to give a ½-in. sand bottom to the flask. The pattern was placed upright on this bottom sand directly in the center of the flask. The remainder of the sample was poured in around the pattern, and the flask, containing the pattern and sand, was raised a height of 4 inches and dropped. This jolting was repeated fifteen times. The sand was then packed evenly across the top and around the pattern with the small wooden rammer, and the pattern was rapped slightly and drawn. This completed the mold for Sample A. Other samples were treated in a similar manner.

As soon as possible after completion, the mold was poured with molten gray iron. The temperature of the metal when poured was approximately the same for each mold in a set. The casting was allowed to stand for 24 hours in the sand, then removed and cleaned. The sand was carefully removed from the casting and mixed with the remainder of the sample. Each batch of sand was carefully saved and mixed with sufficient distilled water to bring the moisture back to 7 per cent. After tempering 24 hours, bond strength, permeability and moisture determinations were again made on the sample, and the sand was rammed up again and the casting test repeated. This process was repeated until the bond strength of the sand became 75[*] or less on the majority of the sands.

9. *Methods for Measuring Comparative Thermal Conductivity of Molding Sands and Effect of Heat on Clays and Sands.*—The comparative thermal conductivities of the molding sands were obtained by inserting a thermocouple into a ½-in. hole, 3 in. deep, in the top of the mold, ⅝ in. from the cavity into which the metal was poured in the endurance tests. Observations of temperature were made on the

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[*]Standard and Tentatively Adopted Method of Testing and Grading Foundry Sands (Doty Method), pp. 6 and 46.

metal before it was poured, and after pouring the temperature of the sand was noted at five-minute intervals until a maximum temperature was reached. The time required to reach this maximum temperature was recorded.

In a second test a thermocouple was rammed up in molding sand, using a transite box for a flask. The box, containing the thermocouple with ⅝ in. of rammed Sand A covering it at the point of minimum sand thickness, was placed in a muffle furnace having a temperature of 1600 deg. F. (871 deg. C.). The flask of sand remained in the furnace two hours, the temperature indicated by the thermocouple was recorded, the box removed, and the temperature of the furnace recorded.

Heat effects on the clays used in this investigation were determined by a second series of sedimentation tests. Half-gram samples of dry clays were mixed with 25 c.c. of distilled water and placed in a glass tube 12 in. long and ⅜ in. in inside diameter, stoppered at the lower end. The amounts of sediment at the end of one-minute and two-minute periods were read on a meter stick placed behind the tube. Fifteen minutes after the mixture was placed in the tube the clearness of the supernatant liquid was observed. The clay was permitted to settle and its total volume read on the meter stick. The volume settling in one-minute and two-minute intervals was then calculated as a percentage of the total volume, and recorded. The same tests were made on clays after ignition.

Additional tests were made by igniting samples of molding sand under the same conditions as the clays were ignited and testing the sand for bond strength. These molding sand specimens were spread out in thin layers so that the heat reached all parts of the sample.

10. *Permeability Tests.*—Permeability factors were determined on the sands after each set of castings in the endurance tests. These tests were run in conjunction with the bond strength tests.

V. RESULTS OF PHYSICAL AND CHEMICAL TESTS OF CLAY

11. *Fineness.*—Table 3 gives the results of fineness tests. These results may be misinterpreted unless remarks in this table are noted. Those marked "clean grains" gave the true fineness of the clay; "aggregates" indicated that fine particles formed lumps and remained on the coarse screens, but these lumps could be crushed between the fingers, and showed much finer grains than indicated in the test.

TABLE 3

FINENESS TESTS ON CLAYS

Clay	Grams Remaining on Screen Number							Remarks
	40	70	100	140	200	270	Pan	
A........	1.9	8.0	6.5	7.5	14.6	7.1	53.3	Clean grains
B........	62.4	10.0	3.5	2.6	3.1	1.1	17.2	Aggregates
C........	4.2	13.7	10.1	9.6	12.9	10.0	38.7	Slightly aggregated
D........	22.1	24.0	7.0	6.5	11.9	12.7	12.9	Aggregates
E........	39.8	23.8	6.1	4.6	7.1	3.8	13.6	Pink and blue aggregates
F........	5.7	33.4	11.7	8.9	13.5	13.7	11.5	Adhered to No. 200 and No. 270
G........	50.6	20.2	6.4	3.8	5.5	5.2	7.5	Fairly clean grains
H........	4.5	16.0	7.6	6.9	9.5	4.7	51.6	Clean grains
I........	0.0	0.4	0.9	2.8	14.9	21.9	57.8	Adhered slightly to sieves

TABLE 4

RESULTS FROM IGNITION OF CLAYS

Clay	Loss of Weight on Ignition per cent	Color after Ignition	Moisture Percentage
A....................	9.15	Pinkish Cream	1.5
B....................	7.19	Chocolate	0.5
C....................	12.44	White	2.0
D....................	12.29	White	4.5
E....................	11.98	Pale Pink	1.2
F....................	14.57	White	1.0
G....................	14.17	Light Chocolate	1.6
H....................	8.58	Pinkish Cream	1.8
I....................	5.33	Cream	16.3

From Table 3 it is evident that Clay I was extremely fine, followed by Clays A, H, C and F in order of increasing coarseness; Clay G was the coarsest. The true fineness of the other clays was more or less doubtful. Six clays were shown to have widely varied degrees of fineness.

12. *Ignition Losses.*—Table 4 gives the loss of weight on ignition, the moisture content of the clays exposed to similar atmospheric conditions, and the color of the clays after ignition. These same colors were evident in the burned molding sands, and show a close relation to the iron content of the clays as given in Table 5, the darker colors being associated with the higher iron percentages.

13. *Chemical Analyses.*—Table 5 gives the partial analysis of the clays used in this investigation. Only the elements commonly ac-

TABLE 5
CHEMICAL ANALYSIS OF CLAYS

Clay	Content, per cent					
	SiO₂	Fe₂O₃	Al₂O₃	MgO	CaO	Na₂O+K₂O
A..........	61.16	2.71	21.17	0.48	0.95	1.07
B..........	56.48	3.53	23.03	0.98	1.10	1.65
C..........	52.82	0.63	33.31	0.14	0.98	0.17
D..........	51.14	0.15	31.53	0.26	0.92	1.80
E..........	50.80	0.48	31.84	0.13	1.39	1.32
F..........	50.74	0.67	45.05	0.09	0.56	0.73
G..........	44.66	2.23	31.19	1.36	1.06	0.87
H..........	56.52	2.23	24.65	0.49	0.67	1.21
I..........	61.54	1.28	23.54	0.37	1.18	3.25

TABLE 6
FUSION POINTS OF CLAYS

Clay	Pyrometric Cone Number	Degrees F.*	Clay	Pyrometric Cone Number	Degrees F.*
A.............	26	2903	D.............	33	3273
B.............	11	2417	E.............	32	3092
C.............	32	3092	G.............	32	3092

*Temperatures corresponding to Standard Orton Cones.

cepted as of importance in clays were determined in these tests. All results are reported as oxides. Using this method it is evident that the total percentages given for a clay will not be equal to 100 per cent. The greatest value of this table lies in the fact that it shows the clays used in this investigation to have had a wide range of chemical content. The table shows that the silica content of the clays varied from 44.66 per cent to 61.16 per cent; the alumina content, from 21.17 per cent to 45.05 per cent; iron, calculated as oxide, from 0.15 per cent to 3.53 per cent; total fluxes, exclusive of iron oxide, from 1.29 per cent to 4.80 per cent.

14. *Fusion Point Results.*—While the table of fusion points, Table 6, does not include all the clays, it shows that one of the clays fused at as low a temperature as the fusion point of cone 11, or approximately 2420 deg. F., which is below the temperature of the molten metal used in this investigation, and one of the clays did not fuse until the temperature of the fusion point of cone 33, or 3270 deg. F. was reached. The equivalent deg. F. for the fusing points of the

TABLE 7
ACIDITY OR ALKALINITY OF CLAYS

Clay	Number of c.c. Alkali Required	Number of c.c. Acid Required	Bond Strength Loss after first casting per cent
F.....................	0.7		50.4
E.....................	0.8		30.2
C.....................	1.5		20.0
I.....................		0.8	10.8
H.....................	3.5		4.8
A.....................	2.3		3.7
G.....................	4.9		3.0
B.....................		Neutral	0.0

TABLE 8
COLLOIDAL CONDITION OF CLAYS

Clay	Remarks
G.....................	Entirely clear at end of 117 hours
D.....................	Supernatant liquid opalescent at end of 11 weeks
I.....................	Supernatant liquid opaque at end of 11 weeks

pyrometric cones was calculated on the basis of a heat increase of 150 deg. C. per hour on the cones.

15. *Acidity and Alkalinity of Clays.*—Table 7 shows the results of tests for free acid or alkali in the clays. This table is arranged in inverse order of bond strength loss after first casting (see Fig. 4), which is in direct ratio to resistance to first heat. The fact that this table shows that increased acidity or alkalinity of the clay, except in the case of Clay B, is associated with increased resistance to primary heating is to be noted.

16. *Colloidal Tests.*—Table 8 gives the results of sedimentation tests on three different typical clays. Clay G was a fire clay; Clay D a ball clay; and Clay I, unknown. Clay G is here shown to have settled out much more rapidly than the other clays and to have been the least colloidal in character. Clay I approached a colloidal gel, and Clay D was intermediate in character. The greatest value of this test was to show the wide range of properties possessed by the clays tested in this investigation.
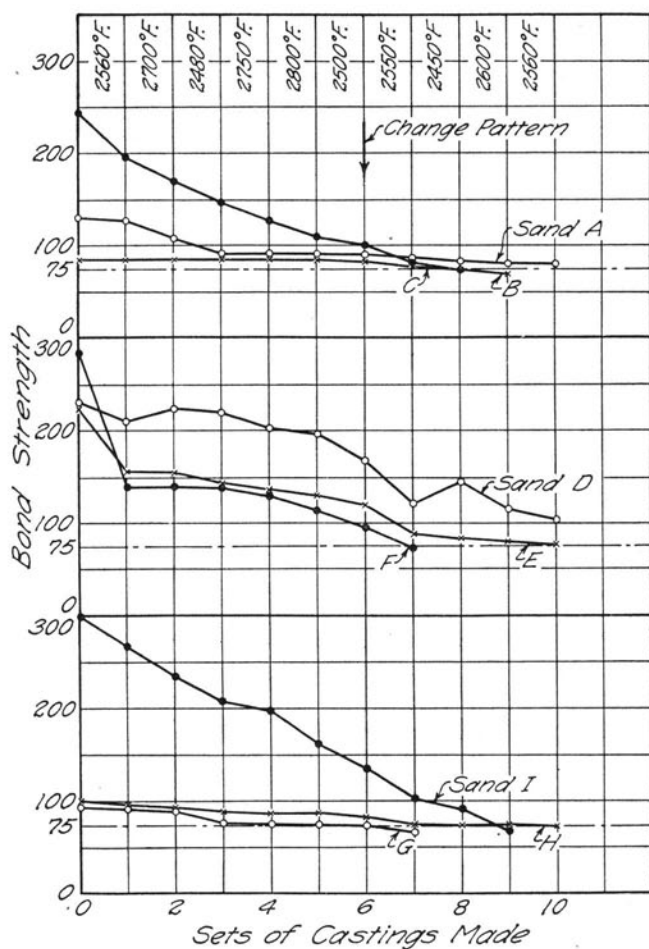
Fig. 4. Results of Endurance Tests

VI. Results of Tests for Endurance of Bond Strength in Molding Sands

17. *Effect of Repeated Casting on Bond Strength.*—The results of the bond strength endurance test can be most effectively shown as curves, and results calculated from the observed data are presented in this manner in Fig. 4.

The temperatures recorded at the top of the graph were those observed on the molten metal when poured into the molds. The tem-

TABLE 9

PERCENTAGE LOSS IN BOND STRENGTH OF SANDS

(After seven sets of castings)

Sand	Loss in Bond Strength per cent	Original Bond Strength	Name of Bonding Clay
B...................	12.5	88*	Shale
H...................	24.2	103	Unknown
G...................	28.3	99	Fire Clay
A...................	34.9	132	Fire Clay
D...................	47.0	234	Ball Clay
E...................	59.6	228	Ball Clay
I....................	65.4	304	Unknown
C...................	68.1	245	Fire Clay
F...................	73.9	288	Ball Clay

*Original bond strength for sand made from powdered Clay B was 135.

perature readings were inserted here for the purpose of comparison, but they do not seem to have any material effect on the loss of bond strength. This was to be expected, for when a mold is open on top it soon cools 300 deg. F., and 300 deg. F. in a total of 2500 deg. F. constitutes a relatively small percentage and therefore has a relatively small effect on the result.

Sand D was very irregular in bond strength, due, no doubt, to the fact that cleavage planes opened in the bond strength test bars, and made true values extremely difficult to obtain in this test.

The change in pattern, on the whole, decreased the bond strength more rapidly. This seemed to indicate that a heavy casting destroyed the bond strength more rapidly than a light one with larger surface exposed to the sand, probably due to the fact that the larger volume of iron contained more heat.

The bond strengths of two of the sands were so low after the seventh set of castings that further testing was discontinued on them, and it was deemed best to consider this heat as the end of the series for determining comparative results.

Table 9 gives the loss of bond strength on heating the sands seven times, the original strength, and the name of the bonding clay. Sands are arranged in order of endurance of bond strength. From this table it is apparent that the type of clay used as bond, the original bond strength, and the percentage loss in bond strength are related. The type of clay, however, is important only in so far as it determines the original bond strength. The percentage loss in bond strength, or the lack of endurance of the clay as a bond, apparently depends on the original bond strength.
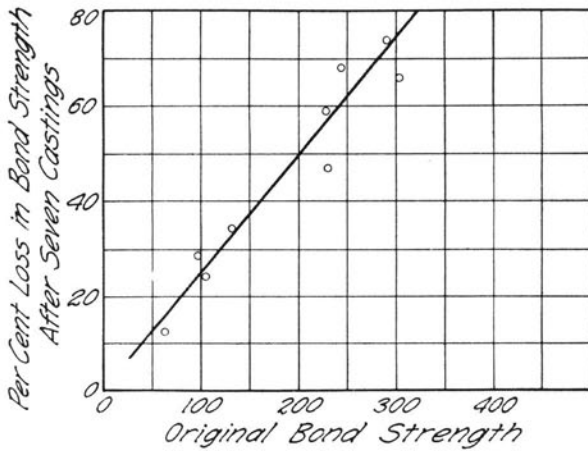
FIG. 5. RELATION OF PERCENTAGE LOSS OF BOND STRENGTH
AFTER SEVENTH CASTING TO ORIGINAL BOND STRENGTH

Figure 5 gives a comparison of the loss of bond strength with the original strength. While a straight line cannot be drawn through all the points, such a relation is indicated, and could possibly be attained if it were possible to conduct the tests under identical conditions, and if a more sensitive means of testing bond strength were available. Unfortunately, this degree of perfection is not at present possible owing to the many factors which must be controlled.

There is a mathematical relation between the original bond strength and the bond strength remaining after seven castings which can be derived from the graph in Fig. 5.

Let the original bond strength $= x$, and the per cent loss of bond strength after 7 castings $= y$

Then

$$y = cx \text{ (equation for a straight line)}$$
$$c = \frac{y}{x}$$

Hence

$$\frac{\text{Per cent of bond strength lost in 7 castings}}{\text{original bond strength}} = \text{a constant.}$$

The values of the constants determined from these tests are given in Table 10, from which it may be noted that the average, with Sand B eliminated, was 0.25. The use of this experimental constant makes

TABLE 10
RATIO OF LOSS OF BOND STRENGTH TO ORIGINAL BOND STRENGTH

Sand	Ratio	Sand	Ratio
A....................	0.264	F....................	0.257
B....................	0.141	G....................	0.286
C....................	0.278	H....................	0.235
D....................	0.200	I....................	0.215
E....................	0.261		

Average ratio (eliminating Sand B) 0.250

it possible to predict the probable loss in bond strength after the 7th casting if the original bond strength of a given sand is known.

Since the value of Sand B, as expressed in Table 10, was decidedly low, additional work was done on this sample. Clay B, having many aggregates, was reduced to a powder in a mortar and triturated wet. After drying out, a new sample B was prepared with the powdered Clay B. Bond strength on this new sample was 135, as compared with 88 on the original sample. In order to determine if the same results could be obtained with the other clays, sample C was treated in the same manner as sample B. The powdered Clay C gave a bond strength of 242, a very good check on the original 245.

It was concluded that Clay B was not all distributed throughout the sand when added as lumps and was only broken up and well mixed after the sand had been used several times, so the original bond strength of 88 was not representative. This latent bond strength explains also why coarse clays are sometimes believed more enduring than fine clays.

18. *Use of Formula.*—By the use of this formula the bond strength of any clay in a used molding sand under given conditions may be calculated without the use of endurance tests. If the original bond strengths of two clays under identical conditions are determined and the residual bond strength of one after certain usage is known the bond strength of the second clay after the same usage may be calculated.

For example, a Clay *m* and a Clay *n* have been tested under identical conditions and found to have the following bond strengths in molding sands, Clay *m* 205 and Clay *n* 150. If sand made with Clay *n* after use in making ten tons of castings has a bond strength of 100, the bond strength of a molding sand made with Clay *m*, with the same proportion of clay and the same moisture content, used under identical

TABLE 11

COMPARATIVE CONDUCTIVITY RESULTS ON SAND IN MOLDS

Sand	Maximum temperature of sand ⅝ in. from casting deg. F.	Temperature of metal when poured deg. F.	Time required to reach maximum temperature min.
A.............	500	2800	25
B.............	520	2800	24
D.............	520	2750	26
E.............	560	2750	25
F.............	550	2700	25
G.............	540	2750	24

shop conditions to make 10 tons of the same class of castings, can be calculated.

$$\text{Clay } n \text{ lost } 150 - 100 = 50$$

and $\dfrac{50}{150} \times 100 = 33.33$ per cent of bond strength lost.

$\dfrac{33.33}{150} = 0.22 = $ constant for the given conditions.

Now, for Clay m, we have

$$0.22 = \frac{\text{per cent of bond strength lost}}{205}$$

$45.1 = $ per cent bond strength lost.

$205 \times 0.451 = 92.46$ bond strength lost.

$205 - 92.5 = 112.5 = $ bond strength which will remain in molding sand made with Clay m and subjected to same treatment as that which left bond strength of 100 in molding sand bonded with Clay n.

The fact that this result was not obtained in previous investigations of endurance of bond strength in molding sands is no doubt due to the fact that these investigations were not conducted under like conditions as to (a) clay content in the sand, (b) moisture content, (c) ramming conditions, (d) temperature of metal poured, (e) base sand, (f) mixing of sands, (g) volume of casting, and (h) cooling time of casting in sand.

VII. RESULTS OF COMPARATIVE THERMAL CONDUCTIVITY TESTS ON MOLDING SANDS AND HEAT TESTS OF CLAYS AND SANDS

19. *Comparative Conductivity Tests on Molding Sands in Molds.*— Measurements of maximum temperatures reached in molds ⅝ in. from castings made on upper pattern shown in Fig. 1 are given in Table 11. These maximum temperatures were in agreement as well as could be expected when it was considered that as much as one sixteenth of an

TABLE 12
SEDIMENTATION TESTS ON CLAYS FOR EFFECT OF HEAT ON THE CLAY

Clay	Before Ignition		After Ignition	
	Per Cent Settled In		Per Cent Settled In	
	1 min.	2 min.	1 min.	2 min.
A............	36.0	44.0	69.2	76.9
B............	32.0	36.0	69.2	76.9
C............	42.3	65.4	71.4	85.7
D............	23.1	34.6	63.5	76.4
E............	75.9	89.7	85.7	92.8
F............	44.8	82.8	77.8	88.9
G............	50.0	72.7	80.0	90.0
H............	40.0	65.0	70.0	80.0
I............	0.0	0.0	65.0	75.0

inch variations, caused by crumbling of the sand, occurred in the thickness of the sand between the thermocouple and the casting. The results in this table indicate that all the sands tested had approximately the same amount of heat transferred to them by conduction. The sand temperatures were very much less than the casting temperature, and the maxima were reached in approximately the same space of time.

The result of the test in which a thermocouple was rammed up in molding sand and inserted in a hot muffle furnace can be summarized as follows:

Sand A covered thermocouple to a depth of 5/8 inch.

Temperature of furnace at start of test = 1600 deg. F. (871 deg. C.).

Length of time sand remained in furnace = 2 hours.

Temperature of sand at end of test = 1300 deg. F. (705 deg. C.).

Temperature of furnace at end of test = 1700 deg. F. (927 deg. C.).

These results indicate that heat is transferred through a mold very slowly.

20. *Effect of Heat on the Colloidal Condition of Clay.*—The percentages of clay settled during periods of one minute and two minutes before and after ignition of the clay are shown in Table 12. It is shown in this table that the clays before ignition had a great range of sedimentation rates; from 0.0 per cent to 75.9 per cent of the total volume of the clays was settled in one minute. After ignition the sedimentation rate was increased on all clays, and tended toward a uniform rate, as shown by the rates for one minute percentages after ignition, where the range was only from 64 per cent to 86 per cent, with an average of 72.4 per cent.
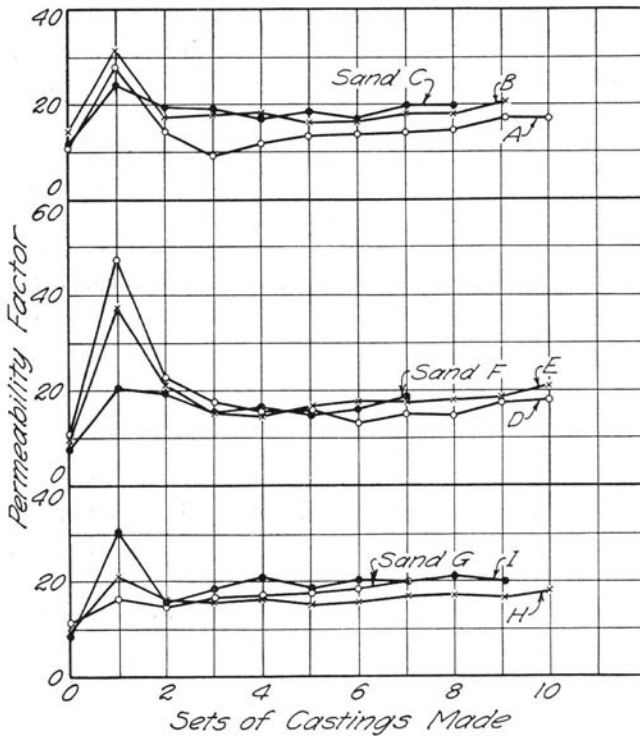
FIG. 6. PERMEABILITY FACTORS AFTER EACH CASTING

21. *Effect of Ignition on Molding Sands.*—The ignited molding sands did not have sufficient bond strength remaining to allow of the making of bond strength tests. This showed that molding sand, where the heat reached all parts, lost practically all of its bond strength in 30 minutes at 1300 deg F. (705 deg. C.), regardless of the type of clay used as bond.

VIII. PERMEABILITY TEST RESULTS

22. *Results of Permeability Tests.*—The graphs in Fig. 6 give the permeability changes in the molding sands caused by each set of castings. The ordinates represent permeability factors and the abscissas the number of castings made in the sand previous to the determination.

The most noticeable feature of these graphs was the rise in permeability after the first casting. This was probably due in part to vitrification, and small lumps or balls present after the first heat. The

lumping here was probably due to fusing of low melting elements and organic compounds in the clay, which broke up and were scattered through the sand on additional heating. Otherwise the curves closely resemble each other in general shape.

The increase in the permeability factor as the bond strength was destroyed was the second most notable feature of these curves. The fact that this same condition is not encountered in the foundry, the reverse being true, the permeability factor decreasing on used sands, is due no doubt to the fact that finely powdered facings are used in the foundry, and the accumulation of the fine material closes the openings between the sand grains. No facings were used in these tests.

IX. Conclusions

23. *Conclusions*.—This investigation included a variety of clays and the results obtained should be applicable to the types of clays now being used for bonding or rebonding molding sands. The following are the principal conclusions:

(1) Abnormal bond strength losses on first heating are related to the alkaline or acidic condition of the clays. These losses, however, adjust themselves to normal conditions on additional heating.

(2) The endurance of bond strength in a molding sand is dependent on the original bond strength of the clay.

(3) The physical and chemical properties of the clay have no appreciable effect on the endurance of the bond strength beyond their effect on the original bond strength.

(4) The type of clay affects the original bond strength but does not, in any other way, influence the endurance of bond strength. This is true only when all factors, except the type of clay, are identical in the composition and the testing of the molding sand.

(5) The endurance of bond strength of a molding sand with any given clay may be calculated, if the endurance under the same conditions of the molding sand bonded with another clay is known, for

$$\frac{\text{percentage loss of bond strength}}{\text{original bond strength}} = \text{a constant for any given set of conditions.}$$

(6) The sand conducts heat very slowly, and only a small shell or envelope of sand in contact with the casting has its bond strength destroyed by the heat. This shell is approximately the

same thickness for any sand, providing the type of clay used as bond is the only variable. This being the case, the loss of bond strength of the sands under these conditions is dependent only on the original bond strength of the clay.

(7) Molding sands lose practically all of their bond strength when exposed to temperatures well below the melting point of the metals cast in them. The reason the sand is not rendered useless by one casting is the fact that the intense heat is not conducted through the sand to any great extent.

(8) In the absence of facing materials the permeability of a molding sand increases as the clay bond is destroyed.

(9) The first heating of the sands causes vitrification and the forming of lumps, which are subsequently broken up and scattered throughout the sand.

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