A STUDY OF SPALLING

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Part I.—Definition and Tests for Spalling

When fire-clay brick are subjected to repeated temperature changes, or to unequally distributed or excessive stresses (in arches) pieces become loosened and the fire-brick are said to spall.

The preceding statement is the generally accepted conception of spalling. The "pinching" of arch-brick is due to improper furnace design and this factor is generally disregarded in testing; hence the various tests involve repeated heating and cooling of the specimens. At certain laboratories the fire-brick are placed in the hearth of the furnace and are heated throughout; at others they are placed in the door of the furnace and are heated on one end only.¹ After the specimens have become properly heated they are cooled either by placing in the open air, by partially or totally immersing in water, or by subjecting to a blast of cold air.

It was not deemed advisable, however, to accept any one of these tests as a temporary laboratory standard without conducting a few preliminary trials. Therefore, batches of fire-brick were secured from four manufacturing centers and were subjected to comparative tests.

The general characteristics of these four brands are given in table 1.

TABLE 1.—PHYSICAL PROPERTIES OF FIRE-BRICK T, S, L AND D

Brand	Per cent porosity	Total end crushing strength	Fusion point in cones	Per cent compression in 1350° C load test	Permanent linear change after reheating 5 hours at 1400° C
T	24.9	2,220	32	5.1	1.1% contraction
S	17.4	5,846	32-33	4	8 expansion
L	24.9	4,235	29	3.2	0.1 contraction
D	28.2	1,890	30	0.2	1 contraction

¹ Nesbitt and Bell, *Proc. Am. Soc. Testing Materials*, 16, 369 (1916).

After the necessary preparation, all of the specimens were heated on one end for one hour at 950°C . One-half of these were cooled by immersing to a depth of five inches for three minutes in 1.5 gallons of cold water. They were allowed to air-dry for five minutes and the process was repeated. The other half of the lot was cooled by subjecting the hot end to an air-blast from the 2.5 inch opening of a 1.25 H. P. centrifugal blower.

The results of these tests are given in table 2 and are shown graphically in figures 1 and 2. The loss of weight is taken as the criterion, and it is evident that both methods place the bricks in the same relative order, although the more severe water-cooling method does not give the finer distinction secured by cooling in air.

Since the two procedures placed the four brands in the same relative order, the water-cooling method was considered the better because of its greater rapidity. Consequently, the following test was finally adopted as a temporary standard:

"The dry test specimen is weighed in grams and placed in the door of a furnace operating at $1300\text{--}1350^{\circ}\text{C}$, care being exercised to prevent the direct heating of more than the 4.5×2.5 inch end. After one hour the specimen is stood on end in a tank of flowing cold water so that the hotter portion of the brick (5 inches) is immersed. When pieces become loosened and fall off, the sample is laid on a 4.5×9.0 inch asbestos board, subdivided into 100 equal squares, and the approximate percentage of loss estimated."

Later it was found that a certain type of checker brick failed after about three immersions in water and that it was necessary to use the air blast in comparing¹ fire-brick of this type.

Part II.—Comparison of Laboratory Tests and Behavior in Service

The previously described test was used in this laboratory for nearly two years, and in every case gave results which were in harmony with the results of experience. During this period of time, however, it received a rather narrow application, for only samples which were made at the same plant were compared at any one time.

¹ A paper on this subject will appear in the near future.

FIGURE ONE
BEHAVIOR OF FOUR BRANDS IN AIR-COOLING SPALLING TEST

FIGURE TWO
BEHAVIOR OF FOUR BRANDS IN WATER-COOLED SPALLING TEST

TABLE 2—SPALLING LOSSES OF DIFFERENT FIRE-BRICK WHEN COOLED BY AIR AND WATER

Number of times cooled	Per cent loss							
	T		S		L		D	
	Air	Water	Air	Water	Air	Water	Air	Water
1	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1
2	.1	.1	.1	.0	.1	.1	.1	.1
3	.1	.1	.1	.0	.1	.1	.1	.1
4	.1	.1	.1	.0	.1	.1	.1	.1
5	.1	.1	.1	4.4	.1	.1	.1	.1
6	.1	.2	.1	.4	.1	.2	.1	.3
7	.1	.2	.1	9.6	.1	.2	.1	.3
8	.1	.2	.1	.6	.1	.2	.1	.3
9	.1	.2	.1	.6	.1	.9	.1	.3
10	.1	.3	.1	.6	.1	.9	.1	19.5
11	.2	.3	.1	.8	.1	.9	.1	..
12	.2	.3	.1	50+	.1	.9	.1	..
13	.2	.6	.1	..	.1	8.2	.2	..
14	.2	.6	34.0	..	.1	40.0	.2	..
15	.2	.6	..	..	.1	..	.2	..
16	.2	.6	..	..	.1	..	0.2	..
17	.2	.7	..	..	.1	..	.2	..
18	.2	1.0	..	..	.1	..	34.0	..
19	.2	.0	..	..	.1	..	..	..
20	.2	.0	..	..	.1	..	..	..
21	.2	.2	..	..	.1	..	..	..
22	.2	.2	..	..	.1	..	..	..
23	.3	.2	..	..	.1	..	..	..
24	.3	.2	..	..	.2	..	..	..
25	.3	.2	..	..	16.5	..	..	..
26	.3	.7	..	..	.5	..	..	..
27	.3	.7	..	..	.5	..	..	..
28	.3	.7	..	..	.5	..	..	..
29	.3	.8	..	..	.5	..	..	..
30	.3	.8	..	..	.5	..	..	..
31	.3	.8	..	..	23.3	..	..	..
32	.3	.8	..	..	.3	..	..	..
33	.3	.8	..	..	.3	..	..	..
34	.3	.8	..	..	.3	..	..	..
35	.3	.8	..	..	.3	..	..	..
36	.3	2.2	..	..	.3	..	..	..
37	..	.2	..	..	..	..	..	..
38	..	.2	..	..	..	..	..	..
39	..	.2	..	..	..	..	..	..
40	..	.8	..	..	..	..	..	..

FIGURE THREE
RELATIVE RESISTANCE TO SPALLING OF SEVERAL FIREBRICKS
MADE AT THE SAME PLANT BUT BY DIFFERENT PROCESSES

FIGURE FOUR
RELATIVE RESISTANCE TO SPALLING OF COARSE AND
FINE GRAINED FIREBRICK OF SIMILAR COMPOSITION

In one instance three processes of manufacture were applied to a certain batch of clays. The resulting product was therefore of practically the same grind and burn, but differed considerably in structure. The results of the tests are given in figure 3, and show the decided structural differences of the different products.

In a second case the clays were ground to different sizes, but the samples were otherwise identical. The spalling test results secured from these specimens are given in figure 4. The advantage possessed by the coarser ground mixture, with respect to resistance to spalling, is evident.

A third citation refers to fire-brick which were made as nearly alike as possible except for hard and soft burning. The comparisons are shown by figure 4 and bring out the superiority of light burned products, from this standpoint, very strikingly.

The results shown in figures 3, 4, and 5 were considered favorable, because in each case they conform to what has been observed. In the following citation fire-brick of widely different characteristics were under consideration, and here the test results showed a decided lack of agreement with what is known to obtain in service. Fire-brick A is usually considered as a "non-spalling" roof brick; C spalls where A does not; B assumes an intermediate position. Other characteristics of these three brands are given in table 3.

TABLE 3—GENERAL CHARACTERISTICS OF FIRE-BRICKS A, B AND C

Ultimate Chemical Analysis	A	B	C
Per cent of silica.....	81.02	55.04	52.95
Per cent of alumina.....	16.58	39.91	42.95
Per cent of ferric oxide.....	1.46	3.65	2.32
Per cent of lime.....	0.40	0.48	0.10
Per cent of magnesia.....	.16	.28	.31
Per cent of soda.....	.32	.40	.67
Per cent of potash.....	.38	.39	.66
Total.....	100.32	100.15	100.20
Fusion point in cones.....	29	32-33	33
Compression in 1350° C load test	1.2%	4.8%	5.2%
Porosity of "run of kiln" brick.....	30.45	21.09	21.00
Porosity after reheating to 1400° C.	32.08	18.43	17.70
Porosity change during reheating...	+1.63	- 2.66	- 2.30
Linear change after reheating five hours at 1400° C.....	0.00	0.15% Exp.	0.61% Exp.

FIGURE FIVE
RELATIVE RESISTANCE TO SPALLING OF HARD AND SOFT BURNED BRICK

FIGURE SIX
SPALLING TESTS ON "RUN OF KILN" BRICKS "A," "B," AND "C."

The results of the spalling tests made upon these three brands are given in table 4 and are shown in figure 6.

TABLE 4—SPALLING LOSSES OF RUN OF KILN FIRE-BRICK WHEN DIPPED IN WATER

Number of dips	Per cent loss		
	A	B	C
2	0.0	0.0	0.0
4	8.0	.0	.0
6	28.0	.7	.0
8	..	2.3	.0
10	..	4.7	.2
12	..	10.7	.5

In view of the facts developing by the preceding examples, the conclusion was drawn that the usual spalling test gives accurate information when the specimens are made from the same fire-clays, but when fire-clays from different districts are compared the results are not in accordance with their behavior in service.

Part III.—Further Development of the Spalling Test

There are two distinct types of fire-clay which, when used in the manufacture of fire-brick, give a product particularly resistant to spalling. The temperature porosity curves for two fire-clays of this nature are given in figure 7, and show that these clays are characterized by a constancy in porosity for a wide range of temperature.

Since clays of this kind undergo only a slight change in porosity when heated, they are considered as being very resistant to vitrification, for decrease in porosity is the best criterion of vitrification.¹

It is also known that when fire-brick spall in service the pieces are usually dense or vitrified. Consequently, the possibility of a relation between vitrification and spalling was suggested. In order to develop this relation, specimens of fire-brick C were prepared by heating for five hours at 1200°, 1300°, 1400°, and 1450° C. This series therefore represented various stages of vitrification, depending upon the highest temperature to which the different samples had been heated.

¹ Brown and Murray, *Trans. Am. Ceram. Soc.*, 15, 173 (1913); Edward Orton, Jr., *Ibid.*, 16, 497 (1914).

FIGURE SEVEN

FIGURE EIGHT
RELATION BETWEEN SPALLING TENDENCY AND TEMPERATURE

The reheated samples were then subjected to the usual spalling test, with water as the cooling medium. When each specimen lost over 33 per cent the number of immersions necessary to produce this failure was recorded as its spalling value. These data were collected and plotted in figure 8, which shows very clearly that resistance to temperature change is a function of vitrification. It is a well-known fact that hard burned (or more completely vitrified) products have a higher coefficient of expansion than those which are soft burned. It has been demonstrated that the harder burned products are also less resistant to spalling. Consequently, it may be that the spalling of fire-clay brick is also associated with thermal expansion, as is the case with silica brick. In the case of fire-brick, however, the thermal expansion will vary with the hardness of burn or completeness of vitrification, and so resistance to temperature change should be considered a function of vitrification.

Vitrification *per se*, however, is not a constant factor, and both the rate and magnitude of the porosity change must be considered. Again, in some cases it may be the result of a predominatingly chemical action, while in others the action is largely physical,¹ and it is probable that no two clays vitrify at the same rate or in the same manner.² Therefore, it is reasonable to expect a change in the relative vitrification of almost any two fire-bricks when heated from 1100°C. to 1400°C. With this thought in mind several samples of A, B and C were heated for five hours at 1400°C. The porosity of C decreased 2.6 per cent, that of B decreased 2.2 per cent, and that of A remained practically constant. C became very dense during reheating, B underwent considerable change, but A showed no visible signs of vitrification.

These reheated specimens were then tested for spalling; one-half of them were air-cooled and the other half were water-cooled. The spalling test results obtained in this manner are given in tables 5 and 6 and in figures 9 and 10.

¹ Brown and Murray, *Trans. Am. Ceram. Soc.*, **15**, 193 (1913).

² See curves. Bleininger and Loomis, *Ibid.*, **19**, 601 (1917).

FIGURE NINE
SPALLING TESTS ON BRICKS "A," "B," AND "C" AFTER
REHEATING 5 HOURS AT 1400°C. AND DIPPING

FIGURE TEN
SPALLING TESTS ON FIREBRICK "A," "B," AND "C"
AFTER REHEATING FIVE HOURS AT 1400°C.
AND SUBJECTING TO THE AIR-BLAST

TABLE 5—AVERAGE PER CENT SPALLING LOSSES OF REHEATED SPECIMENS OF A, B AND C, WHEN COOLED IN WATER

Number of immersion	A	B	C
2	0.0	0.0	0.0
4	.0	.3	.0
6	.3	5.3	44.5
8	23.6	7.0	..
10	..	20.3	..

TABLE 6—AVERAGE PER CENT SPALLING LOSSES OF REHEATED SPECIMENS OF A, B AND C WHEN COOLED IN AIR

Number of treatments	A	B	C
2	0.0	0.0	0.0
4	.0	3.2	6.0
6	.0	19.8	50.0±
8	3.0	Broke after 7	..
10	5.0	..	..
12	39.8	..	..

When the various spalling test results are compared it is obvious that those secured from reheated fire-brick are in close agreement with service data. The position of C is changed entirely and A is given a more correct rating. For some unknown reason B did not give the expected results when reheated and water-spalled; when reheated and air-spalled it assumed the expected position. However, this slight discrepancy is overshadowed by the behaviors of A and C.

It should be noted that A, which is made from open burning fire-clay, underwent but very little change in resistance to spalling when reheated. C, which became very dense in reheating, suffered a radical decrease in resistance to spalling. Another point of interest concerns the fact that the air-cooling method, when applied to reheated fire-brick, gives sufficiently rapid results to justify its adoption.

In summarizing Part III it may be said that a relation has been shown between porosity, vitrification and spalling, for as vitrification increases, resistance to spalling decreases. Since vitrification is associated with porosity decrease it is believed that the following statement is justified:

"Fire-clays which undergo a slight change in porosity when heated over a wide range of temperature have a very slight

tendency to vitrify and are therefore particularly adapted to the manufacture of non-spalling fire-brick."

In view of the preceding results it is also evident that a broader interpretation should be given to spalling and the following statement may possibly meet this requirement:

When portions of fire-brick become loosened in service under the influence of fluctuations in temperature they are said to spall; density due to vitrification, improper brick structure, and unequally distributed stresses facilitate this action.

Part IV.—Application of Porosity-Spalling Theory

Within the past year certain hand-made special shapes, made of two clays used in equal proportions, were found to spall badly in service. When specimens were water spalled, however, they lost less than 3 per cent after twenty immersions. This test proved that the structure of the shapes was satisfactory, and suggested that the clays were at fault. Therefore porosity-temperature determinations were made for clays X and Y and these are given in figure 11. When these curves were examined it was obvious that the dense burning clay Y was more likely to be the cause of spalling than the open burning clay X. The composition of the batch was therefore changed so as to include only 20 per cent of Y, whereas the original batch contained 50 per cent of each clay. The theoretical porosity curve of the original batch is shown as Z and ZZ is the corresponding curve for the revised batch.

The manufactures of these shapes have stated that spalling ceased when the composition of the batch was changed as above suggested. Thus, this case substantiated the porosity-spalling theory, and proved that spalling is not always due to improper fire-brick structure but is largely controlled by the thermal properties of the raw clays.

Undoubtedly this same procedure can be applied to the development of bung brick, glass pot mixes, and any other products that may spall.

Part V.—Application of Results to Testing

In Part II it was conclusively proved that the usual spalling tests give reliable information when applied to fire-brick made from the same clays. It was also shown that tests of this nature

fail when applied to fire-brick coming from different localities. This condition is undoubtedly due to the fact that fire-brick structure is overemphasized by the usual spalling test, while the characteristics of the raw clays are not revealed. The results given in Part IV are ample proof for this statement. Consequently, the development of a satisfactory spalling test is a relatively simple matter for any one manufacturer, but when a consumer buys his product from different sources the problem is more intricate.

FIGURE ELEVEN
POROSITY TEMPERATURE CURVE FOR
CLAYS USED IN SPECIAL SHAPES

However, it is believed that the present investigation has revealed certain factors which can not be neglected in the development of a spalling test. It is essential that the fire-brick be given a severe heat treatment before they are air- or water-spalled. The severity of this treatment should depend upon the service in which the various samples are to be placed.

The objection has been raised that roof brick are heated on one surface only, while in the revised test they are heated throughout. This objection is not considered serious, however, because

of the fact that roof brick which will not vitrify in service will not vitrify in reheating, whereas fire-brick which tend to vitrify will do so both in service and in reheating.

Naturally, a dense burning fire-brick will spall more quickly either in service or in testing, if this characteristic is revealed; with an open burning fire-brick spalling in service is less noticeable and it has been shown that the resistance of specimens of this type to the spalling test is not decreased by reheating (see results secured with A). In other words, the practice of reheating is justified, or condemned, by the presence of, or lack of, a relation between vitrification and spalling. It is believed that this relation has already been established.

A second objection to reheating the spalling test samples lies in the fact that many roof brick are purposely burned "soft" in order to secure the maximum resistance to spalling from a given set of clays. Reheating fire-brick of this type would undo a part of the work of the manufacturer, although treating different specimens in exactly the same manner might still leave them in the same relative order.

So far as can be determined at present there is no possible objection to reheating checker brick (at a temperature equivalent to the working temperature) before subjecting them to the air or water-spalling test.

It is believed that the preceding results warrant the following conclusions.

1. Air-cooling and water-cooling spalling tests give similar results.
2. These results lead to accurate conclusions where the same fire-clays are involved, but misrepresent the facts when different clays are concerned.
3. These discrepancies may be overcome by reheating the test specimen before subjecting it to the spalling test.
4. The necessity for reheating arises from the great differences in the vitrification behavior of different fire-clays.
5. Vitrification is closely associated with spalling.

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