REFRACTORIES UNDER LOAD CONDITIONS¹

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ABSTRACT

Life factors.—The life of fire clay slabs, rings and saggars is influenced by a number of factors, both mechanical and chemical. The chief factors controlling the life of the slabs are (1) proper selections of clays and grog, (2) medium absorption or porosity, (3) strength in the unburned state, (4) proper and thorough blending and preparation of the mix, (5) proper pressing so as to insure freedom from flaws, (6) proper drying, (7) proper setting in the kilns and especially (8) initial burn. These factors are briefly discussed.

Setting.—The manner of setting grinding wheels, using large slabs is described. This manner of setting causes transverse bending stress to be set up in the slab and shear stresses to develop. This shearing force, in connection with the large size and the high temperature (cones 11 to 12), make severe conditions for the slab to withstand.

Shape and size.—The rate of heating and the size and shape of the slabs are additional factors. Round slabs, up to about 20" in diameter have a decidedly longer life when made in two half sections as compared with the solid shape. Larger slabs have longest life when split up into four sections, while if solid they will fail in one burn. Warping of the slabs, as well as cracking, causes failure. In general, if the width of area of the load is held constant, and length of span of the slab is increased, deformation and cracking is slightly increased. If the span is held constant, and the width or load area is increased warpage is greatly increased, especially as the number of burns under load increases. Cracking also increases in direct proportion to increase in width. These features are more pronounced the longer the span.

Ultimate failure at high temperatures.—When not due to structural defects, failure is brought about by a gradual decrease in mechanical strength from burn to burn, so that fire-clay slabs under transverse load at such temperatures have decided limitations.

The ability of fire-clay slabs, rings and saggars to carry load at elevated temperatures is one of importance and concern to many clay working industries, but probably in no industry is it of such vital concern as in the abrasive or grinding wheel industry. This is due not only to the fact that the refractories are called upon to carry heavy loads under rigid conditions, but also because of the large sizes of slabs involved as well as the comparatively high temperatures to which they are subjected.

¹ Received April 16, 1921.

Since grinding wheels varying from a fraction of an inch to 30 inches in diameter are manufactured, slabs to support them in the kiln must necessarily vary similarly in diameter. It is, therefore, customary to use saggers or solid one-piece round slabs up to about 20 inches in diameter for the smaller wheels. The larger sizes are made more economically and are more readily handled if subdivided into two or more sections. Interme-

mediate sizes are, therefore, customarily made in half sections with a ship-lap joint as in figure 1, while the larger sizes are conveniently made in quarter sections as in figure 2.

One of the prime requisites is that of strength in the raw unburned state. With individual slabs weighing from a few pounds up to 150 pounds, the strength in the raw state must be sufficiently great to prevent undue breakage or cracking before the slabs are burned.

The selection of the individual clays and their proper proportions are of no greater importance than the control of the manufacture of the slabs themselves. In fact, experience has demonstrated that the selection of the fire-clays, as long as they are good clays within a safe field of usefulness, is not so important as close attention to the various details in the manufacture. While the usual laboratory tests for shrinkage, warpage, transverse strength, absorption, porosity, et cetera, form valuable guides, the selection of the clays is, however, based primarily upon compromise between these different properties, the undesirable as well as the desirable ones.

All other factors being constant, a slab which is tight and dense, no matter how strong it may be, will, under load, have a short life, owing to its inability to withstand the strains incident to the repeated heating and cooling. A slab which is too open, on the other hand, will be weak and fragile and will not be able to stand either the weight of the load or the strain to which it is subjected. A fairly large field of intermediate density gives slabs which have sufficient strength and hardness to sustain heavy loads and are also porous and open enough to stand volume changes and warpage strains under repeated heatings and coolings.

Figure 3 shows the relation between number of burns before failure and per cent of "goods" for three types of slabs similar in all respects, except that the absorptions were varied by changing the relative proportions of tight and open burning clays going into the mix. Although the degree of vitrification of these clays enters in as a factor, it is slight as compared with variation in degree of openness.

Both the very open slabs and the very dense slabs failed to the extent of 100 per cent in 3 burns at cone 11. The medium porous slabs (10 to 11 per cent absorption), deteriorated much more gradually under the same conditions, the last slab failing in the 10th burn. In fact, a certain amount of strength in the burned state is sacrificed in order that the slabs may be sufficiently open.

The shrinkage of the various clays used is of importance, not only in governing the dimensions of the slabs, but also as a

factor in determining their mechanical strength. The quantity of high shrinkage clays in a mix may be carried to a point where the clay portion will shrink away from the grog to such an extent as to form numerous fine cracks between the grog and clay portion throughout the slab. Outward manifestations of this condition are frequently observed in saggars which have numerous fine hair cracks on their surfaces. The greater the proportion of highly shrinking clays used, the more pronounced does this condition become, and when carried to excess, the slab becomes distinctly lower in mechanical strength. This, therefore, very largely offsets the advantages to be derived from the elimination of low shrinking, high sandy clays, with their attendant volume changes.

The size of grog used in the mix also affects the load-carrying capacity. For slabs which are to carry heavy loads, especially those subject to severe transverse bending, coarse grog is necessary to help keep the body sufficiently open, as well as to prevent excessive shrinkage and cracking. Grog, about 4 mesh to 20 mesh in size, is used to the amount of 50% and all fines are eliminated. Even a small amount of fines in the regular slab mix has a noticeable detrimental effect on the life of the slab. But where the refractories are merely under compression, as in the case of the rings used to support the slabs in a stand, fine grog gives additional strength and is there used to advantage.

Having made a proper selection of clays, usually about 50 per cent plastic tight burning clays, and 50 per cent less plastic open burning ones, it becomes important to secure an intimate mixture. Unquestionably the dry or wet pan gives the best results. Where the ordinary soaking pit method is used, sufficient time must be given for the slaking down of the clays in water and to insure a certain degree of softening in the case of some clays. Thorough pugging of the clay mix is then very necessary. As long as lumps or particles, even though small, of the individual clays used can be distinguished in the mix, the grinding and preparations of the mix are not complete or satisfactory.

The density of the prepared clay mix ready for pressing is also a point to be considered. This density is largely controlled

by the amount of water used in tempering, mixing and pugging. The denser and more compact the structure of the mixture, provided it is not too dry, the harder will be the burned refractory made from it. If too dry, the individual lumps used to make the slab will not press and knit together properly. A mix which is too wet, on the other hand, will not give as dense a structure and as compact a slab as one of proper working consistency.

Pressing of the slabs, especially the larger sizes, is an important operation. Care, and some skill and strength on the part of the presser are necessary to produce a slab free from internal flaws. These flaws are mainly of two types, (1) the more or less long narrow crack within the interior of the slab, sometimes quite wide and not visible from the outside; and (2) holes of varying size or round smooth depressions within the interior of the slab sometimes having small radial cracks leading from them. These flaws are caused by the failure of two or more lumps of clay to become perfectly welded and knitted together when pressed in the mold. The individual pieces of clay remain to an extent. Best practice requires that a lump of clay large enough to approximately fill the mold be used, while exerting a harder pressure also helps.

The dried green slabs, preparatory to the initial burn, must be set in the kiln as tightly and closely together as possible. If they are set even slightly loose and irregularly, they will upon contraction during the burn warp out of shape, which generally renders them unsuitable for further use. Overburning will tend to produce the same undesirable result. Where they are set so as to reinforce each other, contraction will be uniform over their entire area and warping will be prevented. The necessity of having all slabs and saggars perfectly dry before they go to the kiln for the initial burn is obvious, as is also the necessity for a slow water smoking period.

The heat treatment to which the slabs are subjected is of paramount importance, probably more so than any other single operation. Every clay mix has a definite distinct temperature at which maximum strength is developed which in turn largely governs its load carrying ability and maximum service. Slabs requiring a heat in the original burn a few cones higher than

they are to be subjected to later have a longer life than those requiring the same heat for proper maturity. The former are less subject to warping and deformation under load.

Table 1 gives the results of a study made on slabs, free from cracks, of the same dimensions and composition, which were given the heat treatments indicated. The 14 slabs were burned to cone 12 half down to down. The 20 slabs were burned from cone 13 bent to about half down, while the 34 slabs were

TABLE 1

No. of slabs	Initial burn cone	Per cent with no cracks	Per cent slightly cracked	Per cent badly cracked	Per cent broken
14	12	0	21	29	50
20	13—	15	40	35	19
34	13+	38	44	15	3
53	14	68	24	4	4

burned at cone 13 three quarters down to 14 well bent. The 53 slabs were burned to cone 14 down, the temperature required for proper vitrification and best maturity for this particular composition. These temperatures, while not exact, do represent distinct differences in the final heats obtained and the slabs show definite differences in hardness, appearance, etc.

They were then used with loads consisting of regular grinding wheels. Those under the "No cracks" column came out of the kiln with no signs of a crack whatever. "Slightly cracked" slabs were those having a relatively short fine crack, very short large crack or a long very fine crack after drawing from the kiln. These types of cracks in general are not serious enough to cause the slab to break in the succeeding burn. "Badly cracked" slabs are those with a long large crack which generally causes breakage of the slab in question in the following burn.

These results showed conclusively that the initial burning of the slabs is very important and has considerable influence upon their life. Those burned to cone 12 were soft and underburned and can be safely counted upon to last only one burn. Those burned to cone 13 not more than half way down are quite better, although nearly 50 per cent are badly cracked or broken. Those burned to cone 13+ showed still greater improvement, while those burned to cone 14 down showed up very well, only 8 per cent being badly cracked or broken.

Some of the same slabs after close observation and recording of their condition were again placed under regular load, and upon being drawn were re-examined in order to trace the progress in cracking. These results are given in Table II.

TABLE II

	Cone 13—slabs, per cent	Cone 13+ slabs, per cent	Cone 14 slabs, per cent
Crack same as before.....	0	12	54
Increased width of crack.....	55	40	15
Increased length of crack....	31	10	12
New cracks developed.....	14	38	19
Total number of cracks.....	42	40	41

Here again is shown in a striking manner the difference between a well burned slab and one slightly less well burned. Those burned at cone 12 were so poor that it was useless to test them in a second burn. Those at cone 13—, while not appreciably underburned, according to appearance, showed that every slab tested increased in either the width or length of crack. Those at cone 13+ showed that but one out of eight cracks did not increase in width or length and generally the increased length and width of crack was particularly marked. The slabs burned at cone 14 down, on the other hand, showed over 50 per cent remaining in the original condition. Although the cone 13—slabs do not show up newly developed cracks as strongly as the cone 13+ and cone 14 slabs, this is in reality due to the fact that the cracks previously present increased to such an extent as to make it unnecessary for new cracks to develop.

Slabs slightly overfired have a longer life than underfired ones, but not as long as the best. This is largely due to the fact that such slabs are generally slightly warped. The initial burn is, therefore, not only very important but is entirely independent of the subsequent heats to which they are subjected. The practice, so often prevalent, of putting green slabs in odd places in the kiln containing regular ware, where they generally receive the greatest or else the least heat is poor practice. Likewise, the tendency to burn a kiln full of green slabs in a careless manner is just as detrimental to best results.

In setting the kilns with wheels, it is necessary that the bottom slabs be supported upon a firm foundation, consisting of

brick piers at frequent intervals. A thin layer of sand is then spread uniformly over the surface of these bottom slabs. Fire-clay rings are then set around and near the periphery of the slabs, and the grinding wheel is set directly in the center. In the majority of cases, coarse sand is placed between the wheel and the ring, and sometimes the wheel is firmly imbedded in the coarse sand. Another set of slabs is then placed upon the rings, clay wads separating them. A layer of sand, an abrasive wheel in the center and rings on the outside are placed as before, the rings being placed directly in line with rings underneath. This process is repeated for the entire height of the stand.

It will be seen from the manner of setting that the slabs are in compression only at the points where the upper and lower rings are superimposed upon each other, together with the section of the slab between them. The rings together with this small cross section in compression, therefore, carry the weight of all the layers above, whether this weight is that of a dozen or more layers near the bottom or only one set at the top. Since fire clay refractories are able to withstand high compressive forces, as compared to transverse stresses, the refractories seldom, if ever, fail from this source. Each slab or set of slabs, on the other hand, carries the weight of the wheel and its quota of sand, and the greater part of this weight is concentrated toward the center. Since the abrasive wheel occupies the center portion of the stand, no supports of any kind can be placed under the slabs to support them, or to relieve the transverse bending effect. The load applied in the center of the stand, therefore, acts as a shearing force, and a shear is developed when the slab fails. They are all subjected to the same conditions with the exception of the bottom slabs, which are well supported over practically their entire area, and those used on the top of the stand, which carry no load. It is a matter of experience that cracked and warped slabs occur anywhere in the stand, towards the top in about the same ratio as in the center or bottom of the stand, with the exceptions noted.

Since a temperature of cone 11 to 12 is required for the burning of grinding wheels, the slabs are subjected to severe heat treatment in addition to rigid load conditions. A gradual

softening then takes place, as evidenced by warping of slabs of long span, and the mechanical strength is lowered. That increases in temperature have a marked influence on the life of the slab is beyond question. The scrap pile is always larger if the kiln has been burned to cone 12 as compared with cone 11. A quick burn as compared with a slower one to the same temperature also rapidly increases breakage, which is likewise the case with rapid cooling. Warping, cracking and decrease in strength are all increased at a very rapid rate if the burn is conducted under reducing instead of oxidizing conditions.

The smaller slabs are made round and solid, but a point is soon reached where it is more economical to split them into two sections, not only because of increased ease in manufacture and handling, but also because of the increased life. Figure 4, for example, illustrates the relative life of a solid one piece slab of about 20" in diameter compared with that of half-section slabs made as shown in figure 1. Each half section, being in effect a semi-circular slab, then has a greatest length of 20 inches and a maximum width of 10 inches. These slabs were subjected to the same conditions throughout.

It will be seen that the solid slabs cracked excessively under load conditions and that the breakage was very high from the start, all failing in 4 burns. The half-section slabs on the other hand, did not fail at all for a few burns then a gradual failure set in and after several burns the rate of failure increased rapidly. The last half-section slabs to fail did not do so until the 11th burn. The outstanding difficulty with the solid slab is that it generally develops a long crack somewhere towards the center, which frequently divides it into two sections. In doing so, however, it develops additional radial cracks, which soon cause it to break into 3 or more pieces, when it is worthless for further use. When half sections are used the slab not only may be regarded as already being cracked in two pieces, but there is also a decidedly less pronounced tendency for radial cracks to develop, since there is some elasticity in a two-section slab while it is being subjected to expansion and contraction strains, which is not possible in a solid slab.

As the diameter of the stand increases, the dimensions of the

two-section slabs increase accordingly. The maximum length and the maximum width of the semi-circular slabs increase in the definite ratio of 2 to 1, but the effect of these increases upon the tendency to fail is not in a like ratio. A definite slight increase in width plays a greater part in tendency to failure under load than the corresponding double increase in length. This is partly due to the fact that larger, heavier wheels are placed upon the larger slabs, thus increasing the load, but it is due to a far greater degree to the larger area subjected to the load. In general, the wider the semi-circular slab becomes, the greater the tendency to failure from cracking. If carried far enough, these semi-circular slabs become so large that they in turn will crack excessively in one burn and all will fail in a few additional burns.

Because of this and the greater ease of handling, et cetera, the larger slabs are subdivided into four sections as shown in figure 2. A slab, 30" in diameter, for example, if made solid will, regardless of the thickness, not last more than the first burn under load. Indeed, it will crack excessively and in most cases fail, merely under its own weight. If made in two sections, each section has a short life before failure. If made in four sections, however, each section will have a comparatively long life.

Failure, besides taking place through the development of cracks, is also brought about through warping of the refractories. The warping tendency is greatly increased by transverse bending loads, and is always present. In the smaller two section slabs, it is not very pronounced, not only because they are frequently reversed, if they are but slightly warped in one direction; but also because the span is not large. In the large four-section slabs, however, this factor becomes very prominent. The side pieces AA' of figure 2 are especially subject to deformation, because of their long span, since their length is great compared to the width. The superimposed weight on the slab is also unequally distributed, since it is centered in the middle over a comparatively small area. The center pieces BB' are not subject to this deformation in a like degree, since their span is much shorter and the weight of the abrasive wheel upon them is distributed over the greater portion of their area. They would be subject to just as severe a deformation if they were made

as one long center piece across the entire span, but when made as two center pieces BB', they may be regarded as a long center piece already cracked in the middle, so that the warping and cracking tendencies are very materially reduced.

Just as the rate of failure of the half-section slab is increased as the width of the slab increases, so also does this rate increase as the width of the four-section slab increases. This holds true of both the side and center pieces, although the manner of failure is somewhat different, in that warpage or deformation is pronounced in the side pieces, but not in the center pieces.

If the width of the side pieces is held the same and their length or span is increased, deformation and consequent failure is increased in proportion to the increased span. If the span is held constant, and the width, and incidentally the area of the load is increased, warpage of the slabs is very greatly increased. This deformation in general, however, does not take place in the first load burn, but is a gradual accumulation of successive burns, the degree of warpage increasing at a much faster rate in the wider slabs than in the narrower ones. The narrow side piece slabs do not warp to any great extent, even after a number of burns, but will fail from cracking in much the same way as do the smaller half sections. The wide side piece slabs, on the other hand, warp at first very gradually, almost imperceptibly, and then more rapidly. Their load conditions are most severe because in addition to their span, they also are called upon to hold up in place the center pieces with their superimposed loads.

The center pieces have a longer life, since their load is distributed over the greater portion of their area, so that the condition approaches more nearly that of compression, especially in the smaller sizes. In fact the breakage of the smaller sizes is slight, so that they have an almost indefinite life. As the dimensions increase, however, failure increases proportionally. As long as the span between the side pieces does not become great, they will generally fail across or parallel to the width. When the span becomes large, however, the greater proportion crack lengthwise, *i.e.*, perpendicular to the span. If the center pieces become very large, they will fail at a comparatively fast rate, much the same as wide half-section slabs.

The thickness of the slabs plays a rather unimportant part. If they are too thin, they will be too weak to carry heavy loads and to stand any rough handling. Too thick a slab, however, not only requires excess clay, but cracking is increased.

That volume changes play an important part in the deterioration of all slabs is evidenced by the fact that those that have failed after several burns generally exhibit numerous fine cracks, where the clay matrix has shrunk away from the grog. Where the load conditions are such that warping and cracking do not readily take place, the slabs do not give much evidence of this, although such volume changes must have taken place to a lesser extent. That failure in general is due to a combination of causes is seen in the fact that there is no great uniformity in the life of slabs, made of the same mix, in the same way, and subjected to the same size and manner of load. Some will outlive their mates by several burns.

In general, then, in tracing the progress of deterioration of slabs under load at high temperatures, the first slabs to fail are those structurally defective, that is, those having flaws, laminations, et cetera. Then there is a gradual decrease in mechanical strength, due to physical and chemical changes taking place in successive burns, until the point of failure is reached, which in turn is largely influenced by the relation of the load to the strength and position of the refractory. But after all, fire-clay refractories have decided limitations under the conditions given, so that the need of "superior refractories" having constancy of volume, high mechanical strength, ability to carry load at high temperatures, and to withstand sudden temperature changes and which are economical at the same time, is very apparent.

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