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C. W. ROLFE, Director

Effect of Repeated Freezing and Thawing on Brick Burned to Different Degrees of Hardness

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THE RELATION OF HARDNESS OF BRICK TO THEIR RESISTANCE TO FROST.

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INTRODUCTION.

It has long been supposed that the harder a brick is burned, the greater will be its resistance to frost. This is based upon the known fact that with increased hardness of burning, there is an increase in strength and decrease of pore space. In making freezing tests, this supposition has not always been found to be true. The crushing strength has often been found to be most affected by freezing, in the hardest burned brick. In order to determine, if possible, the relations that existed between the hardness of a brick and its resistance to frost, the present investigation was undertaken.

Three series of brick were selected, each series containing four different grades of hardness, and the usual freezing tests were applied. As the investigation progressed, an analysis of the conditions to which the bricks were subjected in the tests and in the wall was begun. This soon led to new ideas concerning the factors involved. Certain additional experiments were therefore made to prove or illustrate these. Because of the lack of definite knowledge of the many principles involved, the discussion is largely theoretical, and represents the belief of the writer. The paper is of a preliminary nature, yet it is believed it indicates the direction in which the truth lies.

The factors involved in the power of a brick to resist frost are the following: The structure of the brick, the disintegrating forces, the conditions affecting the brick in the wall, and the relations between these factors and the durability of the brick. A discussion of the tests now in use and their value follows. The results of the experiments that brought the writer to his conclusions are given, and a summary including the tests believed to be the most valuable in predicting the durability of brick closes the paper.

The writer wishes to acknowledge the kindness of the Departments of Dairying and Applied Mechanics of the University of Illinois for the facilities placed at his disposal for freezing and crushing the brick tested. The kindness of the manufacturers who donated the brick, of Professor C. W. Rolfe, who made the investigation possible, of Professor R. A. Millikan, of the University of Chicago, and of Mr. Ross C. Purdy, who aided the author with criticism and suggestions, are also thankfully acknowledged.

STRUCTURE OF BRICK.

Shape and size of the clay grains. The clay from which brick are formed contains many minerals. Among those that have been identified with certainty are quartz, feldspar, mica, kaolinite, iron oxides, pyrite, and calcite. Of these kaolinite, quartz, feldspar, and mica form the bulk of the clay. The grains of mica and possibly kaolinite originally had the form of flattened plates. These have been so broken during the many changes through which the clay has passed that their thickness often nearly equals their length. The grains of other minerals are approximately equal in all dimensions. With few exceptions, the grains have been worn and rounded by weathering and transportation, and it is not far from the truth to consider them as spherical.

The following mechanical analysis of a clay similar to that from which one of the sets of brick experimented upon was manufactured, illustrates the range in size of the grains.

Mechanical analysis of Champaign subsoil.[1]

Size of Grain	Designation	Percentage
2.000-1.000mm.	fine gravel	1.04%
1.000-0.500mm.	coarse sand	1.98%
0.500-0.250mm.	medium sand	6.85%
0.250-0.100mm.	fine sand	6.23%
0.100-0.050mm.	very fine sand	5.82%
0.050-0.010mm.	silt	28.38%
0.010-0.005mm.	fine silt	15.46%
0.005-0.001mm.	clay	30.00%
	Total	95.76%
Loss on heating, organic matter, water.		4.24%

From this it is seen that the range in size of grain is considerable, but the most noticeable thing is the preponderance of the finest grains,—which form 73.84% of the whole.

Pores. Schlichter,[2] in discussing the origin and relations of pore-space in sands and sandstone, has shown that it depends upon the size of grains, their uniformity of size, and the manner in which they are packed. The larger pores are produced by the larger and more uniform grains and the smaller ones by those that are smaller and more heterogeneous. The maximum pore-space with a given size of grain results when the grains are arranged in a rectangular pattern, the minimum when in a triangular pattern. In every possible manner of packing, however, there is at least one direction in which the interangular spaces form continuous tubes.

On account of the diverse forms of the grains, these tubes are not uniform throughout their length, but consist of a series of triangular cavities connected at their smaller ends. Owing to the variation of the diameters of the grains, these cavities are not uniform in size, but are smaller or larger as the grains increase or diminish in size.

[1]Leverett.   U. S. Geol. Surv., Monograph 38, p. 163.
[2]Schlichter.   U. S. Geol. Surv., 19th Ann. Rept.

Consequently, the pores have the form of a string of irregular beads rather than that of a continuous circular tube.

Nevertheless, Schlichter has shown that these irregular tubes or pores obey the same laws in regard to the passage of fluids through them as do circular tubes. The internal structure of unburned brick is that of a more or less closely packed mass of sand and clay grains. Therefore the laws of capillary tubes may be applied to such brick without serious error.

Laminations. By whatever method brick are manufactured, numerous cracks and crevices arise, which are relatively much larger in two of their dimensions than in the other. For instance, when clay is forced through a die, certain portions of the column move faster than the rest and, slipping along definite planes, form fractures and cracks. The cracks formed by the blades of the auger may not heal, or they may act as planes upon which the clay slips as it passes through the die. Air bubbles confined in the clay are squeezed out flat and remain in the brick. Whatever their origin, the cracks are of similar appearance and are known collectively as lamination cracks.

Lamination cracks, in contrast to pores, are scattered irregularly through the brick, and are but rarely in direct contact with one another. They are, however, connected by the all-pervading system of pores. The pores and lamination cracks together make up the total pore space of the brick, and their size and abundance determine in an important degree its durability.

Effect of method of manufacture and water used in making brick. The manner in which the grains of clay are packed in a brick is determined in a large degree by the method of manufacture and amount of water used in making. In soft mud brick, for example, enough water is added to the clay to form a film around each grain. The grains are separated from each other by this film, and settle together when the brick is dried. The larger grains act as a sort of skeleton and prevent shrinkage to a considerable extent. The grains are, therefore, arranged in a rather open

manner, and the pore space approaches the maximum value possible with the size of grain present.

In the stiff mud brick, on the other hand, only enough water is added to the clay to allow the machine to handle it. The clay is under heavy pressure as it passes through the die, and the grains are crowded together, making the brick compact and dense. When these bricks are dried, there is not the opportunity for the small grains to settle that was present in soft mud brick. As a result, the pore space approaches the minimum limit. The pores are therefore smaller in a stiff-mud brick than in a soft-mud brick made from the same clay. This is illustrated by the shale brick used in the present tests.
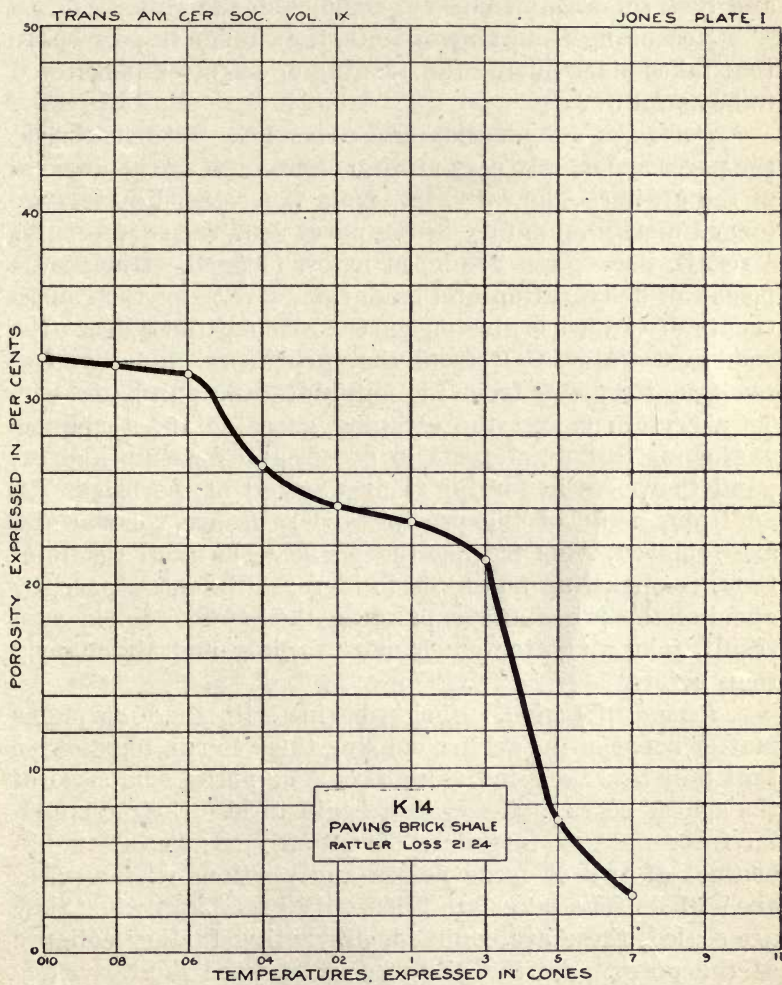
Effective diameter of pores. Although the pores are far from being uniform in diameter, yet it is possible to consider them as being so. This uniform diameter would be that which would allow the same amount of fluid to flow through the pores when the amount of pore space and other conditions are the same. This will be spoken of hereafter as the effective diameter of the pores. This term is analogous to the effective diameter of grain defined by Schlichter.

CHANGES IN PORE SPACE DURING THE BURNING OF THE BRICK.

Purdy and Moore[3] in a study of the physical changes that take place during the burning of brick, found that porosity increases during the period of dehydration and oxidation, and decreases during the period of fusion. One of the clays upon which they worked, was the shale from which two of the series of brick used in the present experiments were made. A curve, taken from their results, shows graphically the decrease in pore space during the period of fusion. (See figure No. 1, which is the same as Fig. XLIX of the Purdy-Moore series.)

In the same paper, is included a microscopic study of

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[3]See page 204.

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PAVING BRICK SHALE
RATTLER LOSS 21 24

POROSITY EXPRESSED IN PER CENTS

TEMPERATURES, EXPRESSED IN CONES

a series of test pieces at different stages of burning, made by Wegeman. His observations showed that with the fusion of the material, the pore space apparently increased, and took the form of blebs or bubbles in the glass.

Reasoning from known facts, the change in pore space that takes place during the burning of the brick is believed to be as follows:

Period of dehydration and oxidation. In dried brick, the pores are mostly very minute on account of the fineness of the grains. The salts, left from the escaped water, are lodged most abundantly in the pores near the surface. As a result, these pores are more or less clogged. During the period of dehydration and oxidation, several of the constituents of the brick give off gases. Among these are: the combined water, CO_2 from the carbonates, and carbonaceous matter, SO_2 from the sulphides and sulphates, etc. To a certain extent the escaping gases act in a manner analogous to that of yeast in bread, and open up and expand the pores in forcing their way out of the brick. In addition, many of the precipitated salts are volatile and are removed, thus freeing the pores. The final result of those co-operating factors is to increase the pore space, by opening the pores and expanding them. The brick, as a result, take up water much more rapidly and abundantly than before.

Period of fusion. Fusion begins with the amorphous matter between the grains, causing them to run together so that they lose their individuality. The pores, composed of the spaces between the grains, begin to lose their triangular form and grow smaller. Eventually the walls come in contact at two or more points and portions of the pores are sealed. The pores are filled with gases, and when they are sealed, these are confined, preventing further collapse of the pores. As the glass becomes more fluid, surface tension causes the gaseous inclusions to take on a spherical form. These minute bubbles, as they come in contact with each other, merge and form larger bubbles. The writer believes that these last are the blebs, described by Wegemann.

When the pores are not completely sealed by glass, they are nevertheless obstructed, and their effective diameter decreased. As will be shown later, this has an important bearing upon the rapidity with which they absorb water, and therefore upon the durability of the brick. It is probable that the only decrease in actual pore space comes about through shrinkage of the brick, and collapse of the unsealed pores. Much of the apparent decrease is due to the sealing of portions of pores by glass, and consequent isolation of these parts from the all-pervading system of pores that existed in the unfused brick. The pore space is commonly measured by the amount of water a brick can absorb, and only that portion of the total pore space is included which offers a free passage to water. This leaves out of consideration the minute and sealed pores, and the apparent decrease in a large measure represents these.

The changes, then, that take place in pore space during burning are: First, the enlargement and clearing of the pores during the period of dehydration and oxidation resulting from the volatilization of the obstructing salts and the mechanical effect of the escaping gases; second, the obstruction of the pores by glass formed during the period of fusion, and the partial or complete isolation of the pores included in the fused portions of the brick.

CHANGES IN STRENGTH AND RIGIDITY DURING BURNING.

As brick are burned, they gain in strength, as has been shown by numerous crushing tests. This is due to the better consolidation of the grains of clay, and the more perfect contact that is produced by their partial fusion with increased heat treatment. The brick gains in tenacity, therefore, and develops greater resistance to disintegrating forces as burning progresses.

Along with this increase in strength, goes increased rigidity and consequent brittleness. While it takes a greater initial force to start disruption in the harder burned brick, the distance through which the force must

act in order to cause complete failure is lessened. This is caused by the fact that hard brittle substances cannot be strained as far without breaking, as the softer and tougher materials. This has an important bearing upon the resistance a brick offers to disintegration by frost.

As an illustration, consider the conditions and action of a brick in the wall of a burning building. The sudden change of temperature expands the surface of the brick more rapidly than the body, on account of the slowness with which the heat is conducted to the interior. When water is thrown upon the wall the surface is cooled very much more rapidly than the interior. The surface of the brick becomes relatively smaller than the body, and a stress results between them. If this stress is great enough to overcome the resisting strength, and the amount of contraction is enough to exceed the elastic limit,—or the distance which a brick may be strained without injury—the brick gives way and spalls off. If the amount of contraction does not exceed the elastic limit, the brick is not injured, since the strained parts return to their former positions as soon as the stress is removed. A little brick has a small elastic limit, and will often fly to pieces under conditions where a softer brick will stand. The harder burned brick, therefore, have the greater initial strength to resist strains, but give way more rapidly after movement is once started.

Tensile strength versus compressive strength. The distance through which the walls of the pores are forced by the expansion of freezing water depends upon whether the tensile strength of the brick is greater than the compressive resistance, or vice-versa. As an illustration, consider a pore near the surface of the brick. If the tensile strength is the weaker, the material at the surface will give way and spall off. As a result the pore will expand in but one direction, i. e., towards the surface. If, on the other hand, the tensile strength is the stronger and the material holds, the pore will have equal pressure on all sides and expand in all directions.

If the pores be considered as circular tubes, this fact may be stated quantitatively. Representing the radius of the pore as r and its length as l, the volume of the pore will be "$l\pi r^2$." Representing the expansion of water as "a" the total expansion of a filled pore will be "$al\pi r^2$." If the expansion takes place in one direction only, as in the first case, the distance that part of the wall must move is equal to the total expansion of the confined water divided by the length of the tube, or "$a\pi r^2$." That is, the distance the wall of the pore is strained is in this case proportional to the square of the radius.

If, as in the second case, the expansion takes place in all directions, the distance any part of the walls move is the total expansion divided by the number of directions of movement, or

$$\frac{al\pi r^2}{2l\pi r} = \frac{ar}{2}$$

That is, the distance the walls of the pore are strained is proportional to the radius. This indicates that the distance any part of the wall of a pore moves in consequence of the expansion of the water, is much greater in the first case than in the second. The chances are much greater, therefore, that the elastic limit of a brick will be exceeded when it possesses greater rigidity than tensile strength.

The actual expansion in a brick probably lies between the two values given, and depends not only upon the size of the pores, but the rigidity of the brick also. In the softer brick, which are less rigid, the expansion of the walls will be more nearly proportional to the radii of the pores. In the harder brick, on the other hand, in which rigidity is greater, the expansion will be more nearly proportional to the square of the radii. The advantage gained by the smaller pores of harder brick is in a measure offset by their increased rigidity and smaller elastic limit.

Special case of the salmon brick. Purdy and Moore

have called attention to the fact[5] that some clays disintegrate and slake when placed in water, becoming plastic again even after having been burned to the temperature of 1100 degrees F for many hours. They explain this phenomenon as due to the action of adsorbed salts, and it may be possible that this is more common than is at present supposed. If this is true, the rapid weathering of some salmon brick is easily explained. In all harder burned brick, however, this factor does not enter, as the adsorbed salts are changed to a harmless form at the temperature at which dehydration and oxidation is finished. Consequently, it may be omitted in the discussion of the brick burned beyond this stage.

The changes that take place in the strength of brick during burning are, therefore, increase in tenacity, due to consolidation and amalgamation of the clay grains; increase in rigidity and brittleness; increase in durability due to change of adsorbed salts to a harmless form. The increase in strength increases the initial strain the brick can withstand, and the increase in rigidity decreases the elastic limit and, therefore, the distance the parts of the brick can be strained without injury.

DISINTEGRATING FORCES DUE TO CHANGE IN TEMPERATURE.

Factors inherent in brick. Brick, which are merely artificial stones, have many characteristics in common with rocks and many known facts concerning building stones may be applied to bricks. Every geologist is familiar with the immense amount of disintegration that rocks undergo from simple changes in temperature. This is especially true in situations, as on mountain slopes, where diurnal changes are rapid. Merrill[6] cites several observations of the effect of rapidly changing temperature on rocks. He tells of finding numerous fresh chips and flakes in the valleys and on the slopes of a mountain in Montana, that

[5]See page 213, this volume.
[6]Rocks, Rock Weathering, and Soils, p. 181.

could only be accounted for by the action of rapid change in temperature during day and night. Another observation he quotes is that of Livingston, who reported that rocks in Africa were frequently heated to a temperature of 137 degrees Fahrenheit during the day, and that rapid cooling during the night split off fragments weighing as much as 200 pounds. The fundamental cause of this disruption is the poor heat conductivity of the rocks.

Rocks and clay products are poor conductors of heat. A difference in temperature of 100 degrees may arise in a depth of one inch when a rock is simply heated by the rays of the sun. The coefficient of expansion of rocks is approximately .000005. In a rock 100 feet long when the above conditions exist, the difference between the length of its heated surface and that of a zone one inch lower would be nearly one-half inch. This places the rock under a tremendous strain, and since rocks are very rigid, the strain is concentrated at the weakest point. Eventually the strain becomes greater than the rock can bear and it gives way.

This same principle operates on brick, and is apparent in the chipped surfaces of a brick wall that has passed through a severe fire. Under ordinary circumstances, the greatest difference in temperature exists between the faces of a wall heated to room temperature on the inside and cooled to the temperature of the air on the outside. This difference is at a maximum during winter and probably amounts to 100 degrees F. Since, however, the bricks are separated from each other by much weaker mortar joints, the wall does not act as a single unit, as a rock mass does, but as a multitude of units. Therefore the differential expansion or contraction cannot be concentrated upon a weak point as it is in rocks, but is confined to each brick. The difference in length of the outer and inner surfaces of a brick under these circumstances is only .0025 of an inch. This certainly does not exceed the elastic limit of the brick and need not be taken into account. The same process that is so effective in disrupting the rocks is ineffectual in brick under ordinary conditions, simply because

their small size and elastic connections render it impossible for cumulative strain to concentrate at any one point.

A factor operative in the crystalline rocks, especially of the coarse grained granite type, is the internal strains set up by unequal expansion of the different minerals. Here (as above, the amount of differential strain depends directly upon the size of the grains, increasing as the size of the grains increases. As most of the material that forms brick is very fine grained and becomes more homogeneous with burning, this differential strain is too small to have any effect.

Factors foreign to the brick. Since it has been shown that there is nothing inherent in brick that will cause their weakening with ordinary temperature changes, the disrupting factor must be some external substance that may find entrance into them and, by its different rate of expansion, set up strains. Of necessity this must be a substance that is fluid at least at the time of its entrance into the brick. The conditions require that it be mobile and able to flow through the pores. Further, it must have a different rate of expansion from that of the brick, in order that a differential expansion and consequent strain may exist with change of temperature. In order that this may be effective as a disrupting force, it is further necessary that the substance be confined to a considerable degree, so that the strains will not be relieved by reverse flow of the substance.

Liquids and gases fulfill the first two conditions perfectly, but as the same properties that permit their entrance into the brick also allow their escape, they cannot cause strain that will mechanically harm the brick under ordinary conditions. All three conditions are only fulfilled by some substance that, fluid at the time of entrance, becomes rigid with change of temperature, or other ordinary conditions, and thus renders it impossible for the brick to confine it.

Of the three states of matter, solid, liquid, and gaseous, only the first is rigid, and the last two fluid. The dis-

rupting substance must, therefore, enter as a liquid or a gas, and then through ordinary change in conditions, become solid within the brick. As at ordinary temperatures, common gases do not reach the solid state, they need not be considered.

A liquid may be solidified by lowering its temperature, by changing the pressure upon it, or by evaporation of one or more of its constituents. When a solid is dissolved, it becomes to all intents and purposes a liquid. Conversely, when it is crystallized from solution it becomes solid again and, if absorbed when in solution, may, upon the evaporation of the solvent, be confined within the brick. Seger[7] states that the concentration of the salts in the surface layer of brick by the evaporation of water often causes the destruction of the surface. Other observers have made the same statement. It would seem at first sight that it would be impossible for a crystallizing salt to exert any pressure or cause any strain, for as the crystal grows it shuts off automatically the supply of solution. It would thus completely close the pores, preventing the further growth necessary to cause strain. Recent experiment[8] has shown, however, that growing crystals can exert considerable pressure and will continue to grow even under considerable resistance. It is possible, therefore, that brick may be injured by the crystallization of salts in the surface layers. It is believed, however, that this is a minor factor in the weathering of brick, and that the greater destruction results from another source.

Some substances, such as water, expand as they pass from the liquid to the solid state. Increase in pressure lowers their freezing point. Consequently, when such a liquid is confined while freezing, the increase in volume will cause a pressure upon the walls of the confining vessel. In order that this may be effective in the brick, it is necessary

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Coll. Writings, p. 372.
G. F. Becker and A. L. Day, Trans. Washington Acad. of Sci. Vol. 7.

that enough of the liquid become solid to seal the surface pores, and thus make it possible for the liquid to be confined while freezing. In so doing, a strain is set up within the brick, which if great enough, may burst its bonds and cause damage.

It is, then, to liquids that expand upon solidification that we may look for the principal cause of the observed weakening of brick by changes of temperature. Of this class of liquids, there is only one that is universally abundant and solidifies at ordinary temperatures. This is water.

PHYSICAL PROPERTIES OF WATER.

Change of volume with change of temperature.

The great majority of substances contract as their temperature is lowered. Water conforms to this rule until the temperature of about 39 degrees F is reached. At this point water ceases to contract and as the temperature is lowered further, expands until it solidifies. Generally solidification takes place at 32 degrees F but may be delayed—as will be explained later—until a lower temperature is reached. This expansion has been measured down to 18 degrees F, and is at this temperature .00186 units.[9] That is to say, one cubic inch of water measured at 39 degrees F becomes 1.00186 cubic inches when cooled to 18 degrees F without freezing. Since water is nearly incompressible, this small expansion of the water, if it were rigidly confined, would cause a pressure of over 500 pounds to the square inch.

Change in volume upon freezing.

When water changes to its solid form, ice, its volume increases approximately one-tenth. That is, ten cubic inches of water at 32 degrees F will become eleven cubic inches when frozen. This increase in volume, whenever the freezing water is confined, may give rise to a pressure upon the walls of the containing vessel that may be great enough to burst it.

Chwolson, Lehrbuck der Physik, vol. 2, p. 134.

Near the close of the eighteenth century, Major Williams, while stationed at Quebec, filled two 13-inch bomb shells with water and closed the fuse holes by driving in as tightly as possible iron plugs weighing three pounds each. The shells were then exposed to the cold of the winter night about twenty degrees below zero F. The next morning one of the shells was found to have burst and a thin fringe of ice projected through and beyond the crack. The plug of the other shells was found at a distance of 415 feet and a column of ice eight inches long protruded from the fuse hole.[10]. Evidently a powerful pressure had resulted from lowering of the temperature of the confined water.

Assuming that all of the water froze, and the shell remained intact, which is possible if the shell was only partly filled, leaving enough space for the ice to form, both shell and ice would contract as they cooled. Since the coefficients of expansion of ice and cast iron are practically the same, whatever pressure may have been within the shell could not change materially. Consequently, if the shell did not give way at the moment the last of the water froze, further cooling could not cause its bursting.

If the water began to freeze and the pressure resulting from the increase in volume of the forming ice became great enough to lower the freezing point of the remaining water progressively with its falling temperature, an increasing pressure would accumulate within the shell as the water cooled. An increase in pressure of one atmosphere —15 pounds to the square inch—upon water will lower the freezing point .01388 of a degree F. The pressure necessary to prevent freezing at 31 degrees F is 1080 pounds, or half a ton, to the square inch; at 22 degrees, 10800 pounds; at zero, 34560 pounds; and at minus 20 degrees—the temperature of the air in Major Williams' experiment—60480 pounds, or over thirty tons, to the square inch. This certainly would be pressure great enough to account for the bursting of the shells. It seems probable, therefore, that

Carnot's Physics, 13th Ed. Trans., p. 320.

part of the water was still liquid at the time the shells burst, and that they were ruptured by the cumulative pressure that prevented this water from freezing.

Moussan[11] performed an experiment that throws some light upon this question. He had a strong cylinder made that was closed at the lower end by a small cone held in by a screw-nut, and at the upper end by a piston moved by a screw-nut. Removing the bottom nut and cone he filled the cylinder with water, placed a bit of copper rod in it as an index, and allowed the water to freeze by exposing the apparatus to the winter air. He then carefully cleaned away enough of the ice to allow him to put the bottom cone and nut in place, screwing them down as tightly as possible. Then he inverted the cylinder and placed it in a salt and snow mixture at a temperature of about zero F. By slowly turning the top screw he compressed the ice to about 0.87 of its original volume. This required about four hours. Then keeping the cylinder in the cold he opened its bottom.

The index at the beginning of the experiment was in the upper part of the ice. If the ice remained solid during the compression, the index should remain in this position and when the cylinder was opened appear last. If the ice was melted by the pressure, the index would sink through the water formed and should be at the bottom of the cylinder, appearing first when it was opened. When Moussan opened the lower screw, and loosened the cone, it came out rather suddenly and ice formed instantly upon its sides. Immediately behind it followed the index and then, for the first time, came a thick cylinder of ice which must have formed at the instant of opening.[12]

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[11] Pogg. Annalen, vol. 105, 1858, p. 170.

[12] "Als man noch diesem Verfahnen die untere Schluss-schraube immer in voller Kälte öffnete, und den klienen Konus löste, trat der selbe sofort etwas heraus und an seiner seite bildete sich augenblicklich Eis. Gleich hinter den Konus folgte der Index und erst nach diesem ein dichter Eiscylinder, der sich im augenblick des Oeffnens gebildet haben musste."

Consequently he had proved that it is possible to melt ice by pressure alone. It seems probable in the light of his experiment that when the enclosing vessel is strong enough to resist the pressure resulting when ice first begins to form, that the pressure lowers the freezing point of the remaining water progressively with its decreasing temperature, and therefore the pressure increases as the temperature is lowered. It has been proven by Tammann and others that if the pressure be great enough and temperature low enough, the ice will change its form, but these conditions are beyond the temperatures and pressures ordinarily prevalent. Recognizing, therefore, that there is a limit, the statement nevertheless holds good that under ordinary circumstances, the pressure resulting from freezing water, when it is confined, increases as the temperature is lowered.

DISINTEGRATING EFFECTS OF FREEZING WATER.

When water is confined, therefore, and cooled below its freezing point, it may cause damage either by its sudden expansion when freezing or from the pressure resulting from its attempt to freeze. The pressure is the same in either case, and since it depends directly upon the temperature at which freezing takes place, may be calculated from the known relations of freezing point and pressure.

Conditions preventing damage. It is evident that if the pores of a brick were filled with freezing water *rigidly confined,* the lowering of its temperature a few degrees below the freezing point would utterly ruin the brick. Yet brick are not ruined in practice, and the largest percentage of loss in crushing strength of a well burned brick that had been subjected to a freezing test was only a trifle over forty percent. Evidently there are mitigating factors effective in the freezing of saturated bricks that have not been considered. These are in part: the pores forming tubes of capillary size permitting the possibility of water not solidifying; the imperfect sealing of the pores and consequent partial relief of the pressure

through outward flow, and the possible draininge of part
of the water before freezing, leaving the pores only partly
filled.

Overcooled water.

As has already been stated, it is possible to cool water
below the freezing point without the formation of ice. The
conditions that favor this overcooling are freedom from
dust and other suspended matter, freedom from dissolved
air, and freedom from contact with ice, and confinement in
minute quantities, as in capillary tubes.

When water is confined in capillary tubes it is possible
for it to overcool further than it would otherwise. By
using boiled and filtered water, Despretz was able to over-
cool it several degrees below the limit given by Chwolson[13],
—18°F—and in the finest tube reached a temperature of
four degrees below zero F, before ice formed. The tem-
peratures reached were influenced by the size of the tubes,
the larger ones freezing sooner.

The influence of ice on the amount of overcooling in
capillary tubes is well illustrated by an experiment of
Moussan's. He placed two series of capillary tubes con-
taining boiled water, in a box, and exposed them to winter
cold which reached a minimum of about 22 degrees F One
series was placed in an inclined position, with one end open
in a vessel of water. The other series was placed in a hori-
zontal position and the ends sealed with shellac to prevent
evaporation. All of the latter series above 1-27 of an inch
in diameter froze. In the series placed in the water and
therefore in contact with ice as it formed in the vessel, only
those smaller than 1-75 of an inch in diameter escaped
freezing. Considering the relatively small amount of over-
cooling in this case, it is evident that only the water in
very small tubes is capable of being overcooled in contact
with ice.

The water in the pores of brick is never free from dust
and dissolved air, and the brick are continually subjected

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[13]Chwolson. Lehrbuck der Physik, vol. 3, p. 592,

shock and vibration from the traffic in the streets and building. The water on the outer face certainly freezes and the water in the pores is in contact with ice as a consequence. On the other hand, most of the pores are very small or at least the numerous constrictions in them produce the same effect.

As there is no method known at present by which the actual freezing of water in the pores can be proven beyond question, we are compelled to depend upon indirect reasoning. It is known that brick suffers a loss in strength by having been subjected to freezing. The amount of this loss increases with the fineness of the pores—as shown by the results of the present freezing tests—and not with their coareness, as it should if overcooling was the dominant factor. It has been shown that there is nothing inherent in brick that will cause this loss, and that the only important cause is the pressure resulting from freezing water. Loss of strength in the brick has been reported in all properly conducted freezing tests, although in these a wide range in the temperatures has been used. It seems extremely probable, therefore, that at least some of the water freezes and causes damage. The amount of damage done, assuming the pores to be full and unable to drain, undoubtedly depends on the temperature and the relative size of the pores, since the finest pores freeze last and at the lowest temperatures. It is possible that a portion of this loss of strength may be due to incipient fractures caused by the rapid and repeated heating and cooling to which the brick were subjected.

Imperfect sealing of the surface pores.

Obviously the power of resistance of the walls of the containing vessel is no greater than that of its weakest point. When, as in the case of the bombshell exposed in Canada, the plug failed before the walls of the shell, the freezing water, instead of bursting the shell found relief by extruding a column of ice through the fuse hole. If a bottle is filled and not too tightly corked, it will present the same phenomenon when the water is frozen. Evidently, if

the pores at the surface of the brick are completely sealed by the first formed ice, the amount of damage done depends plugs or spicules beyond the immediate surface of the brick.

Mosely[14] determined the tenacity of ice as about 100 pounds to the square inch. This was measured as the ice was melting. Andrews[15] measured the resistance offered by a block of ice to penetration by a heavily loaded iron rod at different temperatures. He found that the ice was very hard and resistant, allowing scarcely any penetration, at the temperatures from minus thirty to ten degrees F. At ten degrees it became slightly softer, gradually softening until about twenty degrees was reached. The softening now became more rapid until near the melting point, when it became very rapid. Tammann[16] found that the plasticity of ice is relatively small but increases near the melting point.

It is evident that the resistance offered by the ice plugs when they are first formed is quite small. As the temperature falls, however, their rigidity increases rapidly and when the temperature is lowered sufficiently, may become rigid enough to withstand the pressure of the freezing water in the interior of the brick. The irregular shape of the pores is an important aid to the plugs in maintaining their position at the outlets of the pores. As the cooling of the brick progresses slowly into the interior, the temperature of the ice plugs has probably fallen several degrees by the time the interior water begins to freeze. Taking into consideration, therefore, the increased strength of the plug due to this decrease in temperature, and the extreme irregularity of shape of the pores, it is believed that there is but little relief of pressure due to exuding of the pugs or spicules beyond the immediate surface of the brick.

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[14]Phil. Mag., p. 39, 1870.
[15]Quoted by Barnes, op. cit.
[16]Ann. der Physik, vol. 7, 1902, p. 208.

Partial drainage.

It is evident that if a pore were only nine-tenths full, expansion of the forming ice could take place without injury to the pore. No pressure can arise within the pore until it is more than nine-tenths filled, for this leaves sufficient space for expansion of the ice or water. If, after pores and cavities are filled, it is possible for one-tenth of the water to drain before it freezes, they will be removed from danger of rupture and no damage can result. The two factors that govern the amount of water in the pores and cavities when the plane of frost reaches them are : 1st, the completeness with which the pores are sealed, and 2nd the rate of flow of the water through the pore system.

It goes without saying that if brick are not completely sealed on all sides, the pressure within may be relieved by the flow of the water from the open sides. In freezing tests, as usually conducted, the brick are exposed to cold on all sides alike. As they lose their heat, they cool simultaneously on all surfaces, thereby freezing and sealing the pores on all sides at the same time, and completely enclosing the remaining water within the brick.

In the case of brick laid in the wall, this is not true. The outside face becomes chilled long before the others, and while the pores on the surface are sealed, the others are left open, offering a passage for the water as pressure increases. Consequently the freezing test puts the brick under conditions to which those in the wall are never subjected.

A brick saturated with water and placed in a position where it is possible for it to drain, but where evaporation is prevented, will lose but a very small amount of water. A series of the brick tested were placed, after saturation, in such a position, and at the end of forty-eight- hours had lost but one or two grams of water. Consequently, when the brick are frozen in the freezing can, they do not drain. But as it is impossible to completely saturate brick by soaking, certain parts are free from water. When ice begins to form and the ice plugs have become strong enough to resist the growing pressure of the freezing water, relief

is had by the flow of part of the water into the vacant
spaces. The relative amount of damage done in the brick
depends upon the ease and rapidity with which this is ac-
complished. As the resistance to flow increases rapidly
with the decrease in the effective diameter of the pores, the
finer pored brick should suffer the greater loss in freezing.

Flow through capillary tubes. The pores of the brick
are not of course perfect capillary tubes, but it has been
shown that they obey the same laws. The truths, therefore,
will be at least approximated by considering them as such.

The volume of flow of a liquid through a capillary tube
in a unit of time is expressed by the formula $\dfrac{\pi r^4 p}{8\,u\,l}$ in which
r is the radius of the tube, p is the pressure, or unbalanced
force, at the end of the tube, u is the viscosity, or resistance
to flow of the liquid used, and l is the length of the tube.
Expressed in words, the formula means that the amount of
flow in, say a second, increases sixteen times when the
radius of the tube is doubled, is doubled when the pressure
is doubled, is halved when the viscosity of the liquid is
doubled, and is halved when the length of the tube is
doubled.

The velocity of flow may be determined by dividing
the total flow by the area of the cross section of the tube.

$$\text{Velocity or } V = \frac{\pi r^4 p}{8\,u\,l} \div \pi r^2 = \frac{r^2 p}{8\,u\,l}$$

This means that if the pressure, viscosity of the water,
and the length of the pores were equal, a pore twice the
size of another would transmit water four times as fast.
Therefore the coarser pores of a brick would offer the least
resistance to the flow of water through them.

Effect of laminations upon the durability of brick.
The laminations are irregularly scattered through the
brick, and as a result, the water is not uniformly distri-
buted but the greater portion of it is concentrated in these
cavities. The volume of water in the laminations is enor-
mously greater than that in the pores. Consequently the

amount of expansion due to freezing is not only greater, but it is concentrated at one point. Further, the laminations extend over a relatively large area and so weaken the brick that much more. On account of the greater amount of expansion and the smaller resistance offered by the brick at these points, the greater amount of damage is done by water in the laminations.

The laminations are connected with each other and the surface of the brick only through the pores. The rapidity with which they are filled and drained, is governed by the size of the pores and that alone. As with the pores, the amount of damage that is done depends upon the completeness with which the laminations are filled. Therefore, it follows that the durability of brick depends, not upon the number or size of the laminations, but upon the effective diameter of the connecting pores. As these form the greater part of the total pore-space, it is now clear why the durability of brick does not run parallel to the total pore-space.

As the hardness of brick increases, the effective diameter of the pores decreases, and tenacity and brittleness increases. The effect of decrease in the effective diameter of the pores is to increase the resistance offered to the flow of water through the pores, the increase of tenacity gives greater strength to resist the expansion of the forming ice, and the increased brittleness decreases the limit to which the brick may be strained without rupture. Consequently the harder burned brick may be expected to suffer the greater relative loss in a freezing test, whenever the effects of the smaller pores and the greater brittleness overcomes the increased strength. Even when this is the case, it does not necessarily mean that the harder brick are the poorer, for as a rule their increased strength gives a large factor of safety, and even after they have lost forty percent of their original strength, they are often much stronger than is required.

Relative contraction of brick and ice. After ice is formed, the further damage it will do to the brick depends upon their relative rates of contraction. The coefficient of

expansion[17] of clay wares is .00000457 and that of ice .0000350. This means that ice will contract nearly nine times as fast as brick, and will shrink away from the walls of the pores as the temperature is lowered. *Therefore ice can damage brick only at the time of its formation.*

CONDITIONS GOVERNING THE BRICK IN THE WALL.

The conditions under which brick are placed varies in different parts of the wall. In the foundation, below the water line, brick are subject to continual immersion in water, and under these circumstances must sooner or later become fully saturated. In this part of the wall, there is no chance for any drainage, and the only factors that are called into play are: the total amount of pore-space, and the greatest strength. These bricks are those that have been burned hardest, and in this situation are, beyond doubt, the ones that should be used.

Just above the water line, capillarity determines the amount of water contained. The height at which water stands in a capillary tube, depends upon the diameter of the tube. The smaller the tube, the greater is the height. Consequently, in walls footed in a constant source of supply, water will ascend higher when built of finer-pored brick, than when built of brick with larger pores. The finest-pored brick are the slowest to pass on to the foundation, the water received from above. On this account, also, finer-pored brick are saturated to a greater height above the water line than the coarser-pored bricks. On the other as the conditions are practically those of saturation, the gain in strength of the harder burned brick over the coarser-pored ones, more than offsets the advantage of a narrower saturation zone afforded by the latter.

Above the zone where capillarity is dominant, the brick obtain water only from atmospheric precipitation, and leakage from pipes and gutters. Here the conditions

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[17]Castell Evans, Phys. Chem. Tables, p. 147.

are those of drainage, and the brick that can rid itself of water most quickly is most likely to endure.. The velocity with which water passes through a brick depends entirely upon the size of the pores. Therefore, in this situation, coarser-pored brick should be used, since they transmit water faster.

The three different situations in which brick are placed in a wall are: the saturated zone below the water line, the capillary region just above, and the drainage zone above these. (See figure 1a.) In designing freezing tests, the difference in the situations in which brick are to be placed should be taken into account, and the tests should indicate the brick best suited to each of these positions. This has not been generally recognized, and as a consequence many brick that are well suited for certain conditions are condemned, because the tests used are the same for all situations. Thus the coarser-pored brick, which are really best for situations where drainage is the dominant factor, are unjustly condemned on account of their high porosity. The claim is constantly made that certain building materials will not withstand the frost, simply because they are porous and absorb water rapidly. It is evident that this material, in a position where it can drain, will be freed from danger of freezing much more rapidly than one that absorbs water slowly, and therefore drains slowly.

It is true that the coarser material will pass water through the wall to the interior much more rapidly and abundantly than that which is finer. If the amount transmitted is greater than the air in the interior can absorb, the walls will be damp. This is another problem entirely, and has nothing to do with resistance to frost. Therefore, in considering only the powers of a building to withstand weather, the conclusion is obvious that in situations above the saturated zone, coarser-pored brick are better, provided they are burned sufficiently to remove them from the soft salmon class.

TRANS.AM.CER.SOC.VOL.IX   JONES, PLATE IA
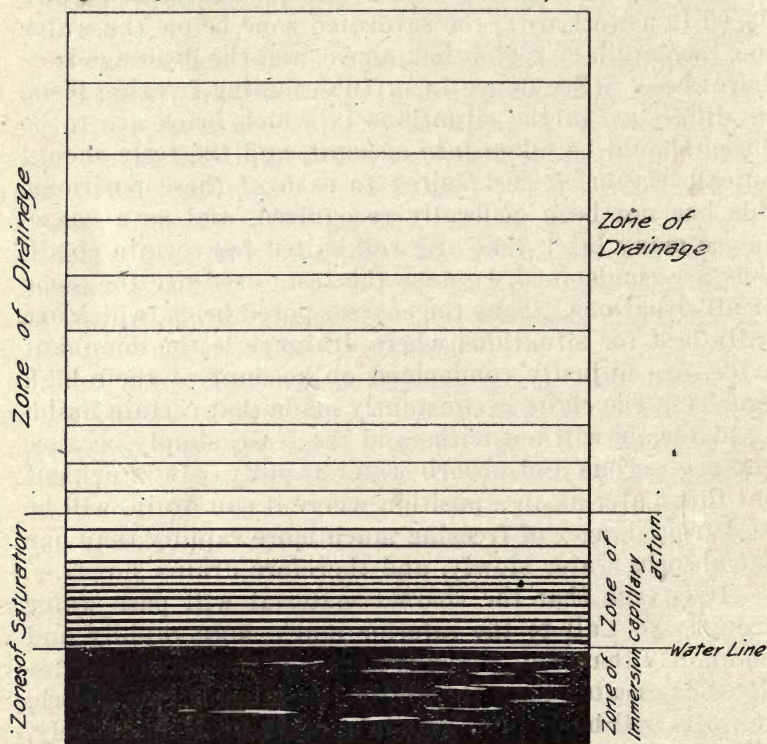
Ideal Sketch Showing Normal Distribution of Water in a Brick Wall.

FREEZING TESTS.

Recognizing the different conditions under which brick are placed in a wall, tests should be designed with these conditions in view. The important factors to be determined in brick to be placed in the zone of saturation, or in similar situations, are total pore-space and strength. The factor of greatest importance in brick to be placed in the zone of drainage, is rate of flow of water through the pores. As long as the brick possesses strength enough to carry its load with a safe margin, further strength is not necessary. The question here is not one of *amount of pore-space*, but *size of pores*. These should be sufficiently large to permit proper drainage, thus preventing damage to the brick by frost.

Methods of determining pore-space. The common method of determining pore-space is to place the brick in water, and after a certain time, determine the amount of water absorbed. This is considered as equivalent to the total pore-space. When a brick absorbs water, it is necessary for the enclosed air to flow out and water flow in through the pores. The rapidity with which this takes place depends upon the effective diameter of the pores. If, during this process, any air remains in the pores and cavities, and is surrounded by the entering water, its only method of escape is by diffusion through the water. This is a very slow process as compared with flow.

It has been observed that a brick will gain in weight when left in water, even after a month's time.[18] Part of this gain is probably due to bacteria, and other minute organisms, that colonize and multiply within the brick. When a surface is exposed to the air, water evaporates, and may deposit salts within the brick. The greater part of the gain, notwithstanding these other sources, is due to the diffusion of imprisoned air, and its replacement by water.

As an illustration of this point, two of the series of brick tested were placed in water three inches deep and

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[18]Wheeler, Mo. Geol. Surv., Vol. 11.

allowed to stand forty-eight hours. After weighing and
re-drying, they were placed in water only one inch deep, for
the same length of time. Using the amount of water ab-
sorbed during deep immersion as one hundred percent, the
percentage of water absorbed during shallow immersion
was found to be as follows:

Kind of Brick	Soft	Med. Soft	Med. Hard	Hard
Soft mud shale	153.2%	120.6%	91.5%	70.9%
Wire cut shale	95.5%	98.5%	43.3%	46.3%

The coarser-pored brick had absorbed much more dur-
ing shallow immersion than during deep immersion, while
the finer-pored had not absorbed so much. When a brick
was deeply immersed, water flowed in from the sides,
above the air in the bottom of the brick, before it had a
chance to escape. Replacement of the entrapped air could
only be accomplished by diffusion. In shallow immersion,
the air had a chance to escape through the pores above, and
was forced out by the ascending water.

Another factor in the experiment is the relation of
flow to pressure. It will be noticed in the formula express-
ing the velocity of flow in capillary tubes $\dfrac{r^2 p}{8\,u\,l}$ that the
flow increases when the pressure is increased. The pres-
sure of the water on the brick was twice as great in the
deep immersion as in the shallow. The water, therefore,
flowed in twice as fast through the pores during deep im-
mersion. In addition, the area exposed for the entrance of
water was nearly three times as great, and therefore many
more pores were available for the entrance of the water.
It is this effect that masks the imprisonment of air in finer-
pored brick, and it was in spite of this that the more rapid
flow and trapping of air took place in the coarser-pored
brick.

Many investigators have maintained that complete im-
mersion is the only natural method by which the relative

porosity of brick should be tested, since it is by soaking that a brick becomes filled, when it is in a wall. It is true that brick in the zone of saturation, where they are continually in contact with water, become saturated by this method. The length of time they are in contact with the water is not taken into account, however, nor the fact that the air imprisoned at the first filling of the pores slowly diffuses until only the amount held in solution by the water is left. Brick in this situation become eventually as thoroughly saturated as if all the air had been removed and replaced by water in the first place. This complete replacement of the air is not possible by complete immersion for the short time given in the usual absorption test. As the only object in finding the pore-space is to determine its total amount, in order to judge the relative durability of brick in situations of complete saturation, the value of this method is small except as a rough test.

Whenever the method of soaking is used, the depth of immersion should be adjusted to the rate of flow of the water through the pores. This is illustrated by the above experiment where the coarser pored brick were more completely filled by shallow immersion, while the finer pored were better filled by deep immersion.

The method that undoubtedly gives the most accurate and concordant results is that proposed by Dr. Buckley.[19] He placed the specimens to be tested, after drying and weighing, in an air tight jar and, after exhausting the air as completely as possible, allowed boiling water to slowly enter and cover the stones. This demands considerable apparatus and is not available for general use on this account. It is possible to approximate the truth by placing the brick, after drying and weighing, in a pan with a small amount of boiling water and boiling them six hours, adding more water from time to time, until during the last hour of the test they are completely immersed. As heat decreases the viscosity of both air and water, the flow

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[19]Building and Ornamental Stones of Wisconsin, Wis. Geol. Survey.

through the pores is accelerated, and the saturation fairly complete at the end of the time. Care should be taken to use as pure water as possible, in order to prevent the precipitation of salts in the brick through evaporation of water from the exposed surfaces. If this should take place the amount of pore-space determined would be more than the true pore-space. Rain water or distilled water is the best.

Calculation of pore-space.

Having determined the total amount of water absorbed, it is possible to calculate the pore-space. In doing this, care must be taken to use the same kind of units throughout. For instance, the common method is to divide the weight of water absorbed by the dry weight of the brick. This cannot give the true pore-space, since it uses the mass of the brick to divide the mass of the water, a substance two and a half times as light, volume for volume. The result thus obtained is too small. To obtain the correct pore-space, the two masses must be reduced to equivalent substances, or volumes, and must be expressed in terms of one or the other.

The simplest reliable method with which the writer is acquainted is one devised by Mr. Purdy.[20] This is, divide the water absorbed by the difference between the wet weight of the brick and its weight when suspended in water. This gives the volume of water absorbed divided by the volume of the brick, or true pore-space. In determining the pore-space of the brick tested, a slightly modified form of this method was used which gave, when carefully executed, nearly as accurate results. The volume was determined by measurement of the three dimensions, and this was used as the divisor of the water absorbed.

Measurement of the rate of flow through pores.

As has been stated, the velocity of flow through capillary tubes is expressed by the formula $\dfrac{r^2 \, P}{8 \, u \, l}$ in which r is

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[20]Page 211 of this volume.

the radius of the tube, P is the difference in pressure at the ends of the tube, u is the viscosity of the fluid used, and l is the length of the tube.   When a brick is placed in water, the force that causes the water to enter and pass into the brick, is the adhesion or attraction of the water for the walls of the pores.   The height that the water will reach, depends upon the mutual attraction of the molecules at the surface of the water, or surface tension.   The force that causes the water to flow is expressed by the formula $2\pi rT \cos a$, in which r is the radius of the tube, T is the surface tension, and a is the angle of contact between the water and the walls of the pore.   The opposing downward force, due to the weight of water raised in the pore, is expressed by the formula πr^2hpg in which h is the height to which the water has risen at any particular instant, p is the density of the water, and g is the force of gravity.   The unbalanced force that causes movement is equal to their difference.

$$Unbalanced\ force = P = 2\pi T \cos a - \pi r^2hpg.$$

Since, in the equation, all of the factors may be considered as constants in the case of the brick and water, excepting r and h, and designating these constants as K and k respectively, the equation may be written

$$P = Kr - kr^2h.$$

Substituting this value of P in the velocity equation, we have

$$Velocity = V = \frac{Kr^3 - kr^4h}{8\,u\,l}$$

Since $8u$ is a constant in this particular case, and l equals h we can write the equation

$$V = \frac{Kr^3 - kr^4h}{K.\,h} = \frac{r^3}{K.} \left(\frac{K}{h} - kr \right)$$

This means that the velocity of the water entering the pores of the brick through capillary action varies approximately as the cubes of the radii of the pores, and inversely

as the height to which it ascends. Consequently a coarse-pored brick will fill much more rapidly than a fine-pored one.

As a test of this theory, the three series of brick used in the freezing tests were placed in water, and the rate at which they filled determined by weighing at intervals of $\frac{1}{4}$, $\frac{1}{2}$, 1, 6, 24, and 48 hours. The first set, the soft mud made from surface clay, were placed in water three inches deep. While some differentiation was shown, it was thought best to set the others in water only one inch deep, and allow capillarity to have full play. As was expected, the differentiation was more marked. The results are as follows:

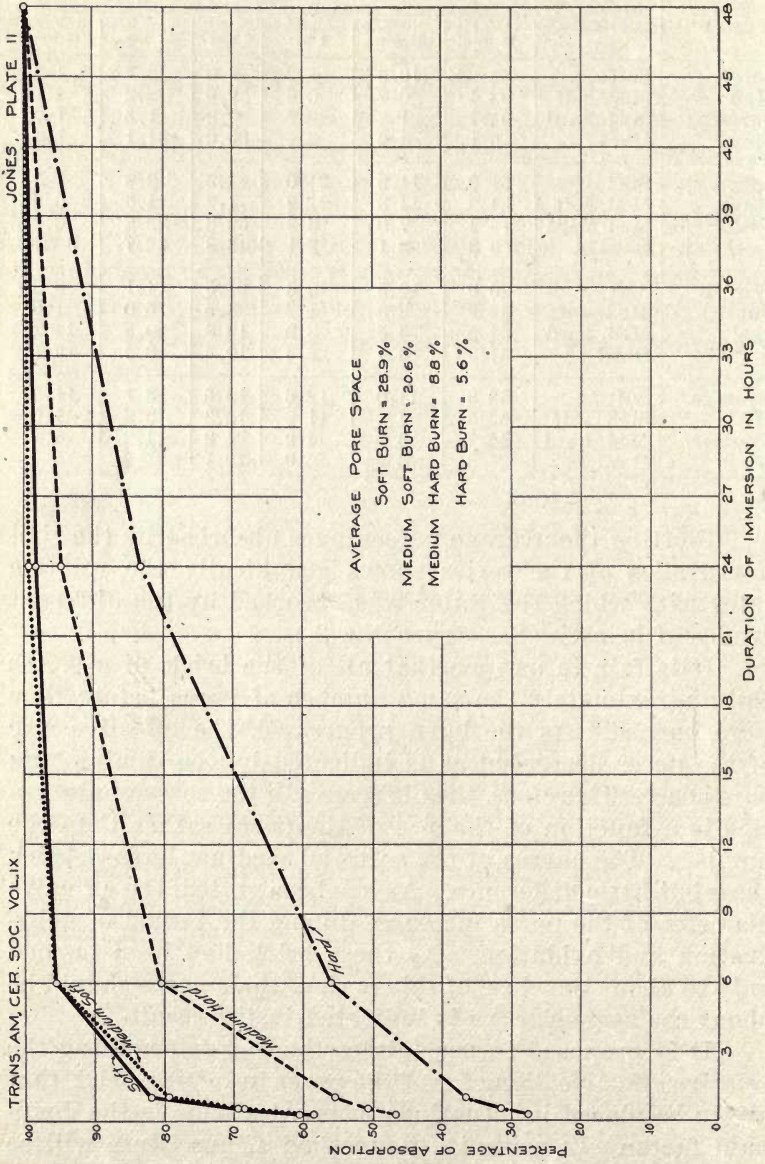| Kind of Brick	Grade of Hardness	Pore Space	Gain						Total abs'b'd.
			15 min.	30 min	1 hr.	6 hrs.	24 hrs.	48 hrs	
Soft mud	Soft	33.0%	369.0	45.3	5.1	8.7	10.5	4.6	442.0
Surface	Med. s't	26.9%	320.9	2.2	2.1	7.1	7.6	3 6	343.6
Clay	" hard	21.2%	237.9	3.1	1.6	7.7	4.6	3.2	258.9
	Hard	10.2%	26.9	4.4	3.9	37.4	33.2	1.7	106.6
Soft	Soft	26.2%	235.1	52.7	94.2	50.4	12.5	4.2	453.1
Mud	Med. s't	17.8	166.8	44.2	68.0	23.7	5.0	1.0	310.1
Shale	" hard	11.6	17.5	9.1	8.1	68.2	26.4	1.0	130.4
	Hard	5.8	4.5	1.0	1.0	6.7	19.2	15 8	48.4
Wire	Soft	27.6%	160.5	40.4	64.1	111.3	16.6	9.1	402.0
Cut	Med. s't.	17.1	78.8	19.4	25.7	89.7	13.7	3.4	233.3
Shale	" hard	2.1	3.8	0.4	0.9	2.2	2 3	1.6	11.1
	Hard	0.9	2.2	0.3	0.4	0.5	0.5	0,7	5.6

Using the total amount of water absorbed by each grade as one hundred, the percentage absorbed during each interval was found to be as follows:

Kind of Brick	Grades of Hardness	Gain					
		15 min.	30 min.	1 hr.	6 hrs.	24 hrs.	48 hrs.
Soft	Soft	83.0%	10.3%	1.2%	2.0	2.4%	1.1%
Mud	Med. soft	93.4	0.7	0.6	2.0	2.2	1.1
Surface	Med. hard	92.1	1.2	0.7	3.0	1.8	1.2
Clay	Hard	25.1	4.0	3.4	35.0	31.1	1.4
Soft	Soft	51.9	11.9	21.0	11.3	2.9	1.0
Mud	Med. soft	54.2	14.3	21.9	7.7	1.6	0.3
Shale	Med. hard	13.4	7.0	6.2	52.3	20.3	0.8
	Hard	9.6	2.1	2.1	13.8	39.7	3.27
Wire	Soft	40.0	10.5	15.6	27.5	4.1	2.3
Cut	Med. soft	33.9	8.5	11.3	38.8	6.0	1.5
Shale	Med. hard	34.5	3.5	8.0	19.3	20.5	14.2
	Hard	47.3	6.4	9.6	10.3	10.3	16.1
Average	Soft	58.3	11.0	12.6	13.6	3.1	1.5
of	Med. soft	60.5	7.8	11.2	16.2	3.3	1.0
Grades	Med. hard	46.7	3.9	4.9	24.9	14.2	5.4
	Hard	27.3	4.2	5.0	19.7	27.0	16.7

Plotting the average percentages absorbed by the similar grades of the series shows graphically the relative rates with which the water was absorbed by the different grades of brick. (See figure No. 2.)

It is fair to assume that all of the brick in a series had approximately the same number of pores before they were burned. As the burn progressed, the effective size of the pores decreased as is indicated by the diminishing pore space. Therefore, the difference in the rates of absorption is a function of the size of the pores rather than the number. The curves of the soft and medium burned brick show but little difference. As has been stated, the effective diameter of the pores increases during the period of dehydration and oxidation. As these brick had been burned only to about the close of this period, their pores should be about the same size, as is indicated in the result.

It is proposed to use this method of determining the relative effective diameter of the pores in testing brick that are to be placed in situations where drainage is the dominant factor. In using it, the method of procedure will be as follows:

AVERAGE PORE SPACE

SOFT BURN = 28.9 %
MEDIUM SOFT BURN = 20.6 %
MEDIUM HARD BURN = 8.8 %
HARD BURN = 5.6 %

DURATION OF IMMERSION IN HOURS

PERCENTAGE OF ABSORPTION

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JONES, PLATE II

(1)   Dry the brick forty-eight hours at a temperature of 300 degrees Fahrenheit.

(2)   Weigh, after cooling to room temperature.

(3)   By room temperature is meant about 75 degrees Fahrenheit.

(4)   Place the brick on edge in water whose final depth after the brick are placed is one inch.

(5)   The temperature of the water is important, as its viscosity changes rapidly with temperature, thus changing the rate of flow. If it is kept at room temperature, or near 75°F in every test, the results may be safely compared. Otherwise a variable factor is introduced.

(6)   At the end of fifteen minutes, remove the brick and weigh, after removing the surplus water clinging to the surface.

(7)   Replace in water for forty-eight hours.

(8)   Weigh as before.

(9)   The percentage of water absorbed in fifteen minutes, using the amount absorbed in forty-eight hours as 100 percent, indicates the relative rate of absorption.

Methods of freezing.

In testing brick to be placed in a position where they cannot drain, as in a foundation, they should be saturated as completely as possible by boiling, or under the air pump, and frozen while standing in water. This will test them under conditions that are similar to those actually occurring. The brick to be placed in situations where they can drain, as in the upper wall, should be filled with water by soaking and placed in a dry can while freezing. These are approximately the conditions under which they will be placed in the wall.

At the temperatures just below freezing, overcooling plays a more or less important part. In tests using these temperatures, the results are uncertain to the extent of the unknown value of this factor. As is indicated by the winter temperature conditions prevailing in Springfield and Chicago, the drop in temperature after a storm is probably to about ten degrees F. It is probable that only the pores

are able to cool to this temperature without freezing. The additional damage resulting from freezing them is at most very slight, and the differential expansion of the brick itself is negligible. Cooling to a moderate extent below this temperature would not materially alter the results. It seems to the writer, therefore, that the temperature of the freezing can should be at least as low as that prevailing in nature, and that average temperatures as low as zero F are permissible. It is best for the comparison of results to keep between the limits given. As it is impossible to control the temperature of the atmosphere, or to obtain uniformly low temperatures during the length of time necessary—twenty days—to conduct a freezing test, a refrigerating plant is a necessity.

EXPERIMENTAL DATA.

As an illustration, three series of brick were selected, a soft mud made from surface clay, a soft mud made from a shale, and a wire cut made from the same shale. An attempt was made in selecting the brick to have in each series four grades of hardness which were designated as soft, medium soft, medium hard, and hard. Each grade of the surface clay was represented by five brick, and each grade of the shale brick by eight. These were selected by eye and by the sound emitted when struck, from the different parts of the kilns, each series coming from one kiln, and were as nearly uniform as was possible to obtain under the circumstances. The selections were made by Mr. Purdy.

Four brick of each grade and series were used in the tests of absorption and freezing. The brick were dried forty-eight hours in an air bath at a temperature of 340 degrees F and weighed, after cooling in the bath to room temperature. They were then placed in water three inches deep, and allowed to remain forty-eight hours, after which they were packed, and covered in a can placed in brine to a depth that brought the surface of the brine considerably above the top level of the brick. The brick were left here from ten to twenty-four hours until they were thoroughly

frozen.   They were then removed and immersed in water
at a temperature of approximately fifty degrees F, until
they were completely thawed out.   This cycle of freezing
and thawing was repeated twenty times.   After the final
thawing, the brick were dried as before, weighed and the
loss due to freezing determined.   The temperature of the
brine averaged two degrees F during the tests, with a max-
imum range from 18 to 24 degrees.   As all brick of a series
were frozen together, this extreme variation did not affect
the comparison of the results.

The brick were then crushed, together with unfrozen
duplicates, in an Olsen testing machine of 200,000 pounds
capacity.   For the crushing test, the brick were first
broken with a hammer and the half-brick used, in order to
bring them within the capacity of the machine.   Where
there was but one brick to crush, as in the case of the
unfrozen ones made from surface clay, both halves were
crushed and the average taken.   The brick were bedded in
plaster of paris and the plaster allowed to set under an ini-
tial pressure of 2000 pounds.   It was impossible to get the
brick bedded uniformly even by this method, and there was
an extreme variation of 400 pounds in halves of the same
brick.   The brick generally failed quietly, although occa-
sionally, especially among the harder ones, they would ex-
plode and send fragments flying ten feet from the machine.

As the number of the unfrozen bricks varied, the num-
ber tested is given in the results.   The results given by the
frozen brick are invariably the average of four specimens.
As it was practically impossible to select specimens in each
grade that would have the same crushing strength, and
since the perfection of bedding necessarily varied in the
different brick, the extreme variation in each grade ranged
from 400 pounds in the softer grades to 4000 pounds in the
harder brick.   Otherwise the tests are quite satisfactory,
and it is believed as nearly accurate as was possible to ob-
tain under the circumstances.

Results of the Freezing Tests.

Kind of Brick	Grade of Hardness	Crushing Strength		No. Tested	Per cent Loss in Strength	Percent Pore Space	Per cent Ab-sorption in 15 minutes	Remarks
		Frozen	Unfrozen					
Soft	Soft	1194	1374	1	13.1	33.0	83.0	Frozen
Mud	Med. soft	3567	3400	1	*4.6	26.9	93.4	Brick
Surface	" hard	4289	5315	1	19.9	21.2	92.1	Scaled
Clay	Hard	7377	7260	1	*1.6	10.2	25.1	on Face
Soft	Soft	2671	2913	3	8.6	26.2	52.9	One Brick
Mud	Med. soft	4625	5793	3	20.2	17.8	54.2	Broken in
Shale	" hard	8522	10143	2	16.5	11.6	13.4	Freezing
	Hard	7606	11470	4	33.8	5.8	9.6	
Wire	Soft	3729	4637	4	19.6	27.6	40.0	Two bricks broken in
Cut	Med. soft	6965	8117	4	14.2	17.1	33.9	freezing.
Shale	" hard	9165	11315	4	19.4	2.1	34.5	Two bricks cracked in
	Hard	115..	11997	4	4.1	0.9	47.3	freezing.

*Gain.

The loss in weight due to freezing was very small, being but a few grams, in most cases, and 2% in an exceptional one.

If these results are arranged in the order of their pore-space, hardness, and rate of absorption as indicated by the percentage absorbed in the first fifteen minutes, the relations of these factors to loss of strength due to freezing is clearing brought out.

Arranged in the order of hardness.

Grade	Surface Clay	Soft Mud Shale	Wirecut Shale	Average of All
Soft	13.1%	8.6%	19.6%	13.8%
Med. soft	4.6*	20.2	14.2	9.9
Med. hard	19.9	16.5	19.4	18.6
Hard	1.6*	33.8	4.1	12.1

*Gain.

As may be seen, there is little relation between the hardness of the brick and its resistance to frost. The surface clay suffered greatest loss when burned medium hard, and their hard burned representatives suffered much less;

the soft mud shale suffered most when hard burned, and the softest brick the least; while with the wire cut shale brick, the soft and medium hard suffered most, and the hard burned much less. Upon plotting the average of the three kinds, the curve zigzags very decidedly, indicating that hardness in itself does not determine the amount of resistance the brick will offer to frost. (See figure 3.)

Arranged as to Porespace.

Porespace	Per cent. Loss.	Average of Similar Groups.	
		Porespace	Per cent. Loss.
33.0%	13.1%	33.0%	13.1%
27.6 26.9 26.2	19.6 4.0* 8.6	27.0	7.9
21.2 17.8 17.1	19.9 20.2 14.2	18.0	18.1
11.6 10.2	16.5 1.6*	11.0	7.4
5.8 2.1 0.9	33.8 19.4 4.1	3.0	19.1

*Gain

Arranged as to pore-space even greater discrepancy than in the former case is seen. The plotted curves zigzag in every instance. (See figure No. 4.) They should be continuous, if there were any relation between the amount of pore-space and resistance to frost. An interesting series of results along this same line is contained in Dr. Buckley's report on the building stones of Missouri[21], in which the same lack of definite relation of amount of pore space and resistance to frost is strikingly brought out.

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[21]Buckley, Quarrying Industry of Missouri, 2nd ser. Mo. Geol. Surv., Vol. 2, Pl. LIX.

TRANS. AM. CER. SOC. VOL. IX   JONES, PLATE III

RELATION OF HARDNESS AND
PERCENT OF LOSS

TRANS.AM.CER.SOC.VOL.IX   JONES, PLATE IV

RELATION OF PORE SPACE AND
PERCENT OF LOSS
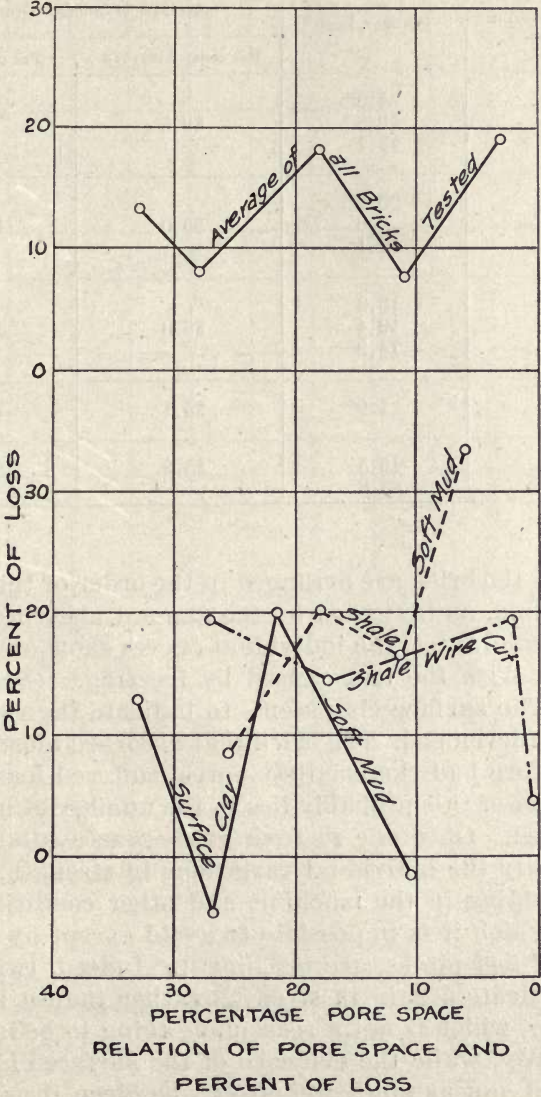
Arranged in the order of their rates of absorption.

Percent absorbed in 15 minutes.	Per cent. Loss	Average of Similar Groups.	
		Per cent. Absorbed	Per cent Loss
93.4 92.1 83.0	4.6* 19.9 13.1	89.5	9.4
54.2 52.9 47.3	20.2 8.6 4.1	50.0	11.0
40.0 34.5 33.9	19.6 19.4 14.2	35.0	17.7
25.1	1.6*	25.1	1.6*
13.4 9.6	16.5 33.8	10.0	25.1

*Gain.

When the brick are arranged in the order of their rates of absorption, as indicated by the amount absorbed in the first fifteen minutes, the individual curves show only slight agreement with the loss caused by freezing. (See figure No. 5.) The surface clay seems to indicate the reverse of the theory developed. The brick that absorbed most slowly, and therefore had the smallest pores, suffered least. The explanation of this probably lies in the number of unfrozen brick tested. Only one in each grade was available, and consequently the individual variations in strength, perfection of bedding in the machine, and other conditions, the effect of which it is impossible to avoid except by using a number of test pieces, are prominent. Indeed, two of the grades indicate a gain in strength rather than a loss due to freezing, which is not a reasonable thing to believe and, consequently, while the evidence of the surface clay brick is accepted, not as much weight can be given it as that of the shale brick which were tested more completely. With

RELATION OF WATER ABSORBED IN 15 MINUTES
AND PERCENT OF LOSS
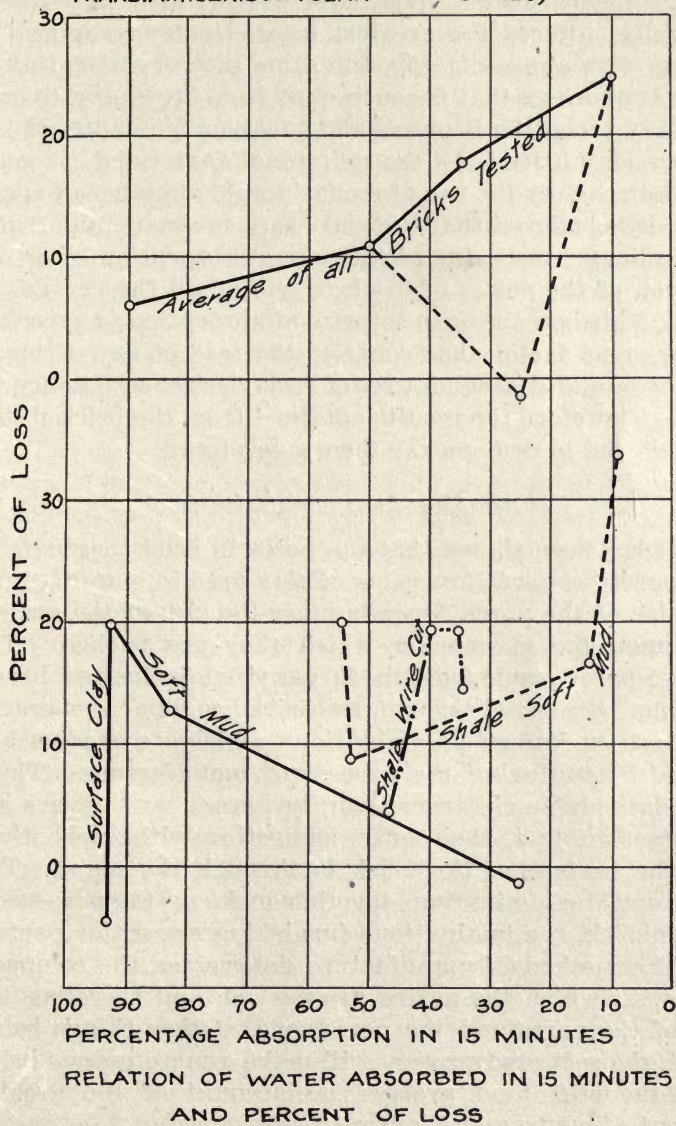
the latter, the finer-pored brick, even though they were not always the hardest or possessed the greatest pore-space, generally suffered the greatest loss. Upon averaging the groups with approximately the same rate of absorption, a curve is obtained that is continuous from beginning to end. The only exception is one of the questionable values of the surface clay brick. As the individual variations can only be eliminated by the use of a considerable number of specimens, it is believed that this curve approximates the truth, and indicates the value of the rate of absorption as an indication of the power of brick to withstand the ravages of frost. This is true, since the rate of absorption is governed by the same factor that controls the rate of flow through the pores, and consequent relief from danger of damage by frost. Therefore the results obtained from the brick tested are believed to confirm the theory developed.

SUMMARY AND CONCLUSION.

It has been shown that the pores in brick originate in the spaces between the grains of clay used in manufacture. The size of the pores depends upon the size of the grains, and upon the manner in which they are packed. The coarser pores result from the larger sized grains and looser packing. Scattered through the brick are numerous cracks and cavities, known as laminations, which are produced in several ways during the process of manufacture. These are relatively much larger than the pores. As they are not in direct contact, their only connection with each other, and the surface of the brick is through the pores. The pores and the laminations together make up the pore-space of the brick, the laminations furnishing the major part.

The method of manufacture determines the compactness with which the grains are packed, and therefore the size of the pores and the pore-space. Other things being equal, the soft mud process will make a more porous brick than the stiff mud process, on account of the greater amount of water and slighter pressure used.

During the water-smoking and oxidation period of the

burn, pores are opened and enlarged by the escaping gases. The bricks have their maximum amount of pore-space at this time, and it remains at this value until the amorphous material begins to melt. When this happens, the grains soften around their borders and run together. This tends to obstruct the pores, and eventually completely closes them at different points along their length. The parts of the pores that are enclosed between the points sealed, contain gas that prevents the further closure of the pore. As the amount of glass increases, the enclosed gases form bubbles which become spherical in shape. These bubbles are completely shut off from the system of pores, and the pore-space apparently decreases. Those pores that are not sealed are obstructed, which is equivalent to making them smaller.

The strength of the brick increases as it is burned, and also its rigidity or brittleness. This gives the brick greater resistance to strain, but decreases the distance it may be deformed without breaking. A given amount of expansion or contraction may, therefore, rupture a rigid brick, when it would not harm a tougher one.

Owing to the universal occurrence and abundance of water, and its property of expanding upon freezing, it is the only substance that under ordinary conditions causes any considerable damage to brick. It expands one-tenth of its volume when freezing, and when it is confined within the brick, may burst it upon freezing. The important factor serving to mitigate the destructive effect of freezing water is the opportunity generally afforded for a portion of the water to drain, before the brick cools sufficiently to freeze. The temperature at which the brick freezes may be blow the ordinary freezing point of water, owing to the property of capillary tubes which delays the freezing of water within them until a lower temperature is reached. It is not probable that freezing in the larger openings is entirely prevented at the temperatures prevalent during the winter months in our northern States.

The amount of water that may drain depends upon the rate with which it passes through the pores. This is deter-

mined by the size of the pores, and is much greater in coarse pores than in the finer ones. It was found that water will pass through pores four times as fast if they are doubled in size, and nine times as fast if they are trebled. Although the lamination cracks contain the bulk of the water, they are dependent upon the pores for drainage. Consequently the amount of damage done in a brick depends on the size of its pores, since this governs the rapidity with which it will drain.

In the foundation at the water line, the brick are continually in contact with water. As any air originally confined in them will eventually diffuse, they become completely saturated. The brick just above the water line are filled through capillary action from below, and from the drainage of the upper wall. These also become completely saturated, and as the frost seldom reaches the water line, it is this part of the wall that suffers most. The amount of damage done the brick in this zone of saturation is proportional to the total pore-space, and the strength of the brick. The best brick for this situation is, therefore, the one that is strongest and least porous.

In the upper wall the brick are able to drain. The amount of damage is therefore proportional to the rate of flow through the pores, and the total amoutn of pore-space has little direct effect. As in freezing, tests giving similar effects are present, it is easy to understand why the hard-burned, fine-pored brick suffered more than those softer, but with coarser pores.

It is of vital importance to consider the future position and conditions in which brick are to be placed, in making tests to determine the ones best adapted. In the situations where saturation is the controlling condition, as in foundations, evidently the brick that contains the least amount of pore-space is the best. In consequence it is necessary to determine the total pore-space, minute pores and all, since these become filled, sooner or later, in saturated situations. This cannot be done by the method of soaking at present used, but may be approximated by boiling or the use of the air pump.

In situations where drainage is the controlling factor the brick that will drain fastest is the best, if injury from frost only is considered. The relative rate with which the brick will drain must be obtained. This may be easily done by the method proposed on page 39.

The crushing strength of brick has an important value in foundation brick, as it indicates the relative resistance the brick will offer to expansion of the freezing water. The brick in the upper wall, on the other hand, need only the strength necessary to carry their load.

Consequently these three tests,—total pore-space, rate of flow through the pores, and crushing strength,—should give a correct indication of the power of a brick to withstand frost. In the brick to be used in situations of saturation, only pore-space and strength need be determined.

The characters of the brick which are altered during burning are: the size of the pores, the amount of pore-space, the strength of the brick, and its rigidity. The harder burned brick have finer pores, a smaller amount of pore-space, greater strength, and greater rigidity. They therefore drain more slowly, contain a smaller amount of water when filled, have greater strength to resist the expansion of freezing water, but will rupture with a smaller amount of expansion. Whether or not the hardest burned brick will resist frost best, depends upon the relation between its gain in strength and loss of pore-space on the one hand, and the decrease in the effective diameter of its pores and increase in brittleness on the other. If the former factors are progressively altered more rapidly during the burn than the latter, the harder burned brick will be the more durable. If, on the other hand, the latter factors are the ones to develop more rapidly, the power of resistance of the brick as the burn progresses is relatively decreasing. The quantitative expression of this relation has not been worked out, and must be left for some future investigator. The present investigation, however, has shown the direction in which the relation between hardness and resistance to frost may be found.