Practical Proportion of Salt. Since in practice it is impossible to tell how low the temperature will fall before the concrete sets, Mr. Thompson has adopted the arbitrary rule of 2 pounds of salt to each bag of cement to be used when the temperature is expected to fall several degrees below freezing, and if experience shows that this is not quite sufficient to prevent the frost catching the surfaces, 3 pounds of salt per bag of cement are to be used instead.

The salt can be added most conveniently by putting it into the mixing water. To determine the amount of salt per barrel or per tankful of water, the quantity of water used per bag of cement must be noted and from this the amount can be readily figured.

Calcium Chloride. Experiments indicate that calcium chloride added in quantities not exceeding 2% of the weight of the cement is an effective agent for lowering the freezing point of the concrete. It should be used with caution, however, since a larger quantity than this is likely to so hasten the set as to make the concrete difficult to handle.

CHAPTER XVIII

FIRE AND RUST PROTECTION

Observations of steel imbedded in concrete which has been exposed to fire or to corrosive action, and experimental tests prove conclusively that 1½ to 2 inches of dense Portland cement concrete, made in ordinary proportions, with broken stone, gravel, or cinders, of good quality, and mixed wet, will effectually resist the most severe fire liable to occur in buildings, and will prevent the corrosion of steel even under extraordinary conditions. In members of inferior importance or which are only liable to fire of comparatively low temperature, a less thickness of concrete, in many cases ¾-inch or even ½-inch, will prove effective. (See p. 333.)

In buildings concrete has been found a more effective fire-resisting material than terra-cotta (see p. 333) and fully equal to first-class brickwork. Brickwork cannot exist in a structure except in combination with some other material like steel or wood, which is seriously affected by fire, whereas concrete reinforced with steel may replace not only the brickwork, but also the steel or wood columns and beams.

PROTECTION OF STEEL BY CONCRETE

Tests by Prof. Charles L. Norton

Extended practical tests have been conducted by Prof. Charles L. Norton for the Insurance Engineering Station in Boston. As a result of experiments made in 1902 upon several hundred specimens, he concludes:*

(1) Neat Portland cement, even in thin layers, is an effective preventive of rusting.
(2) Concretes, to be effective in preventing rust, must be dense and without voids or cracks. They should be mixed quite wet where applied to the metal.
(3) The corrosion found in cinder concrete is mainly due to the iron oxide, or rust, in the cinders, and not to the sulphur.
(4) Cinder concrete, if free from voids and well rammed when wet, is about as effective as stone concrete in protecting steel.

In his first series of experiments, round rods of mild steel, soft shee steel, and expanded metal were each imbedded in the center of blocks of

*Engineering News, October, 1902, p. 334.

concrete, 3 by 3 by 8 inches. Neat cement, 1:3 mortar, and concrete in proportions 1 cement : 5 broken stone; 1 cement : 7 cinders; 1 cement : 2 sand : 5 broken stone; and 1 cement : 2 sand : 5 cinders, were employed for imbedding the steel. The stone was chiefly of trap rock. These specimens, after setting, were subjected continuously to the action of steam, air, and carbon dioxide. Unprotected pieces of steel were also exposed to the same test.

At the end of three weeks the unprotected pieces of steel "were found to consist of rather more rust than steel." The protection of the steel incased in neat cement was perfect. The remaining specimens, in mortar and concrete, were seriously corroded in spots, but it was observed that the "rust spot was invariably coincident with either a void in the concrete or a badly rusted cinder. In the more porous mixtures, the steel was spotted with alternate bright and badly rusted areas, each clearly defined." One point is exceedingly instructive:

> In both the solid and the porous cinder concretes, many rust spots were found, *except where the concrete had been mixed very wet, in which case the watery cement had coated nearly the whole of the steel, like a paint, and protected it.*

Protection of Rusty Steel. In 1903, Prof. Norton made tests to determine the protection afforded ordinary rusty or dirty steel. He found that while unprotected steel "vanished into a streak of rust," if protected by an inch or more of sound concrete, not only the sound steel but ordinary structural steel of any degree of cleanliness likely to be in use in a building is unaffected by such extreme treatment as was accorded it in the tests. The conditions of these later experiments were similar to those of the previous year. Each piece of steel was stamped, and this removed loose scale. Dirt was removed by a soft wire brush. The steel was imbedded to a depth of 1½ inches in all directions in broken stone concrete of proportions 1:2½:5 and in cinder concrete of proportions 1:3:6. The treatment of the specimens was similar to that of the previous ones.

A portion of Prof. Norton's conclusions* are given in the following paragraphs:

> **Condition of Specimens.** After varying lapses of time from one to three months for the specimens in the "corroders," and from one to nine months for the others, the specimens were broken out of the briquettes cleaned by brushing, and weighed and calipered. Not one specimen had shown any sensible change in weight or dimension, except where the concrete had been poorly applied. Some specimens were purposely bedded in very dry concrete, and some in concrete partly set, and many of these were not well covered and the steel was seriously attacked where there were voids or cracks. Of the hundreds of specimens of rusty steel examined, not one which had a continuous unbroken coating of concrete gained or lost anything in volume or weight by treatment which caused the practical destruction of some of the unprotected specimens. If loss by corrosion as great as 1-1000 of the loss occurring with the unprotected specimens had been experienced in the case of the protected pieces it would have readily been noted.
>
> **Conclusions.** It would therefore seem that if we admit that from a severe trial of a short duration, we may judge relatively of the effects of the less severe but longer test of time, it can not be questioned that structural steel is safe from corrosion if incased in a sound sheet of good concrete, at least for a period of years so long as to make the subject of more interest to our great-grandchildren's children than to us. We know that bare steel does not rust and fall down over night, and that much of the steel standing has been bare of everything that could protect it, for long years, and it seems to me beyond question that steel properly covered in concrete may well be expected to last far longer than the changes in our cities will allow any building to remain.
>
> **Protection by Cinder Concrete.** There is one limitation to the whole question, that is the possibility of getting the steel properly incased in concrete. Many engineers will have nothing to do with concrete because of the difficulty in getting "sound" work. This is especially true of cinder concrete, where the porous nature of the cinders has led to much dry concrete and many voids, and much corrosion. I feel that nothing in this whole subject has been more misunderstood than the action of cinder concrete. We usually hear that it contains much sulphur and this causes corrosion. Sulphur might, if present, were it not for the presence of the strongly alkaline cement; but with that present the corrosion of steel by the sulphur of cinders in a sound Portland concrete is the veriest myth, and as a matter of fact the ordinary cinders, classed as steam cinders, contain only a very small amount of sulphur. There can be no question that cinder concrete has rusted great quantities of steel, but not because of its sulphur, but because it was mixed too dry, through the action of the cinders in absorbing moisture, and that it contained, therefore, voids; and secondly, because in addition the cinders often contain oxide of iron which, when not coated over with the cement by thorough wet mixing, causes the rusting of any steel which it touches.
>
> **Mix Wet.** There is one cure and only one, *mix wet* and mix well.* With this precaution I would trust cinder concrete quite as quickly as stone concrete in the matter of corrosion.
>
> **Rust no Protection for Steel.** It has been suggested that steel which has been rusted to a slight depth becomes protected by this coating from further rusting. Nothing could be further from the truth. A large num-

**Engineering News*, January, 1904, p. 30.

*See page 280 for the authors' definition of a very wet mixture.

ber of specimens were rusted by repeated alternate wetting and drying to see if they finally reached a constant condition. Instead of doing this, they all showed an irregular but persistent loss in weight, on further rusting, until some had practically been washed away.

Small Rods. The increasing use of steel of small dimensions in floors and roofs, twisted rods, expanded metal, etc., has caused some question as to the advisability of their use in view of the possible great effects of corrosion, as compared with the effects of corrosion on larger members, but with sound concrete of a thickness of about 1½ in. between the steel and the weather I do not question the durability of these lighter members.

CHEMICAL UNION OF STEEL AND CEMENT

Experiments of Mr. Breuillé* indicate that clean steel may form with cement a chemical combination which is soluble in water. This presents an additional reason for making concrete in which steel is imbedded as impervious as possible, to avoid the penetration of moisture which will wash away this chemical compound, if such is found to exist in actual structures. Large I-beams imbedded in concrete would be especially subject to deterioration from this cause, but as rust rarely forms between two plates of steel which are riveted together in a bridge, even although the rest of the structure is badly corroded, the danger is probably insignificant.

Cement Paint for Protecting Steel. The property of neat cement which prevents steel from corrosion is taken advantage of in different forms of cement coating. Mr. Maximillian Toch in 1903† made a series of experiments upon metal covered with various preparations of cement, and drew the following conclusions:

(1) A proper cement paint can be applied to a surface that has begun to oxidize, and further oxidation will be arrested.

(2) If the cement be absolutely fine and free from iron, calcium sulphate and sulphites, and of low specific gravity, it will set on the surface within a very short time, and eventually become an integral part of the metal.

For exposed iron work Mr. Toch recommends a protective coat of cement paint followed by a coat of linseed oil paint. To protect from the fumes of a factory, he states that after applying three coats of cement paint, an alkali-proof, adherent paint may be spread, and an absolute protection afforded to the iron.

Mr. J. W. Schaub‡ refers to the use of cement mortar in Europe and in

*J. W. Schaub in Transactions American Society of Civil Engineers, Vol. LI, p. 124.

†Lecture on the Permanent Protection of Iron and Steel, delivered before the New York Section of the American Chemical Society, March 6, 1903.

‡*Engineering News*, June 16, 1904, p. 561.

the United States for coating iron exposed to destructive agencies. He says:

The mortar is usually a mixture of 1 cement and 2 sand, applied with a brush as a wash. Five or six coats are applied in this way to give the metal a proper coating. This is especially applicable in the case of the iron work exposed in roundhouses, where the gases from locomotives are so destructive, and where paint is so inefficient.

FIRE PROTECTION

Numerous experimental tests* have been made showing the value of concrete as a fire-resisting material, but the best proof of its ability to resist the heat of a severe fire — such as is liable to occur in an office or factory building — lies in the fact that concrete has actually withstood very severe fires more successfully than have terra-cotta and various other so-called fireproof materials.

The reinforced concrete factory of the Pacific Coast Borax Co. at Bayonne, N. J., passed through a severe fire in 1902. Still more recently, in 1904, occurred the conflagration at Baltimore in which many building materials utterly failed.

Such practical tests, further confirmed by numerous experiments with test buildings of reinforced concrete, have proved that while in a severe fire, where the temperature ranges from 1600° to 2000° Fahr., the surface of the concrete may be injured to a depth of from ½ to ¾ inch, the body of the concrete is unaffected, so that the only repairs required consist of a coating of plaster, and even this only in rare instances.

Tests upon small briquettes of cement placed in a furnace indicate that the strength of cement is destroyed by a heat reaching a dull, red color,† but as stated below, in an actual fire, the injured material protects the rest of the concrete so that the danger is theoretical rather than real.

Fire in Borax Factory. The fire in the 4-story reinforced concrete factory of the Pacific Coast Borax Company, built entirely of concrete except the roof, utterly destroyed the contents of the building, the roof, and the interior framework, but the walls and floors remained intact except in one place where an 18-ton tank fell through the plank roof and cracked some of the floor beams, and in one place on the outside of the wall where the surface of the concrete was slightly affected. The fire was so hot that brass and iron castings were melted to junk. A small annex,

*See References, Chapter XXIX.

†Digest of Physical Tests, Vol. I, p. 217.

built of steel posts and girders, was completely wrecked, and the metal bent and twisted into a tangled mass.

Baltimore Fire. The effect of the fire upon the concrete in various buildings located in the center of the burned districts of Baltimore is best appreciated by an examination of the reports of experts upon the fire. Capt. John S. Sewell, in his report to the Chief of Engineers, U. S. A.,* in referring to the fire in one of the buildings built with reinforced concrete columns, beams, and arches, writes:

It was surrounded by non-fireproof buildings, and was subjected to an extremely severe test, probably involving as high temperature as any that existed anywhere. The concrete was made with broken granite as an aggregate. The arches of the roof and the ceiling of the upper story were cracked along the crown, but in my judgment very slight repairs would have restored any strength lost here. Cutting out a small section — say an inch wide — and caulking it full of good strong cement mortar would have sufficed. The exposed corners of columns and girders were cracked and spalled, showing a tendency to round off to a curve of about 3 in. radius. In the upper stories, where the heat was intense, the concrete was calcined to a depth of from ¼ to ¾ inch, but it showed no tendency to spall, except at exposed corners. On wide, flat surfaces, the calcined material was not more than ¼-inch thick, and showed no disposition to come off. In the lower stories, the concrete was absolutely unimpaired, though the contents of the building were all burned out. In my judgment, the entire concrete structure could have been repaired for not over 20% to 25% of its original cost. On March 10, I witnessed a loading test of this structure. One bay of the second floor, with a beam in the center, was loaded with nearly 300 pounds per sq. ft. superimposed, without a sign of distress, and with a deflection not exceeding ⅛-inch. The floor was designed for a total working load of 150 pounds per sq. ft. The sections next to the front and rear walls were cantilevers, and one of these was loaded with 150 pounds per sq. ft. superimposed, without any sign of distress, or undue deflection.

Captain Sewell concludes as a result of the examination of this and other buildings containing reinforced concrete construction:

As the material is calcined and damaged to some extent by heat, enough surplus material should be provided to permit of a loss of say ¾-inch all over exposed surfaces, if the structure is to be exposed to fire; moreover, all exposed corners should be rounded to a radius of about 3 inches. This latter precaution would add much to the resistance of all materials used in masonry — whether bricks, stone, concrete or terra-cotta — if they are to be exposed to fire.

*Engineering News, March 24, 1904, p. 276.

Concrete Versus Terra-Cotta. Prof. Norton, in his report on the Baltimore fire to the Insurance Engineering Experiment Station,* says:

Where concrete floor arches and concrete-steel construction received the full force of the fire it appears to have stood well, distinctly better than the terra-cotta. The reasons I believe are these: First, because the concrete and steel expand at sensibly the same rate, and hence when heated do not subject one another to stress, but terra-cotta usually expands about twice as fast with increase in temperature as steel, and hence the partitions and floor arches soon become too large to be contained by the steel members which under ordinary temperature properly enclose them. Under this condition the partition must buckle and the segmental arches must lift and break the bonds, crushing at the same time the lower surface member of the tiles.

When brick or terra-cotta are heated no chemical action occurs, but when concrete is carried up to about 1 000° Fahr. its surface becomes decomposed, dehydration occurs, and water is driven off. This process takes a relatively great amount of heat. It would take about as much heat to drive the water out of this outer quarter-inch of the concrete partition as it would to raise that quarter-inch to 1 000° Fahr. Now a second action begins. After dehydration the concrete is much improved as a non-conductor, and yet through this layer of non-conducting material must pass all the heat to dehydrate and raise the temperature of the layers below, a process which cannot proceed with great speed.

Cinder Versus Stone Concrete. Prof. Norton compares the action of stone and cinder concrete in the Baltimore fire as follows:

Little difference in the action of the fire on stone concrete and cinder concrete could be noted, and as I have earlier pointed out, the burning of the bits of coal in poor cinder concrete is often balanced by the splitting of the stones in the stone concrete. I have never been able to see that in the long run either stood fire better or worse than the other. However, owing to its density the stone concrete takes longer to heat through.

Further experiments are required to determine the relative durability under extreme heat of concrete made with different kinds of broken stone. It seems probable, from the composition of the rock, that hard trap or gravel may be preferable to limestone, slate, or conglomerate as fire-resisting material.

Thickness of Concrete Required to Protect Metal from Fire. The conclusion reached by Prof. Norton† from tests upon concrete arches is that two inches of good concrete gives perfect assurance of safety in case of fire, even if the steel to be protected is in the form of I-beams. Rods of

*Engineering News, June 2, 1904, p. 529.

†Insurance Engineering, Dec., 1901, p. 483.

small dimensions can be more effectively coated, and it appears evident from the various tests and from practical experience in severe fires that 1½ inches of concrete around steel rods is sufficient protection. The Pacific Borax Company's fire and other similar tests indicate that in slabs of reinforced concrete, ½ inch to ¾ inch affords ample protection. Secondary members, such as cross girders, or slabs of long span, should have a thickness of concrete outside of the steel varying from ¾ inch to 1½ inch. Although in slabs protected by only ½ inch of concrete, the latter may be softened by an extreme fire, and the metal exposed when it is struck by the stream from a hose, the metal in the majority of cases would still remain practically uninjured, and it is questionable economy to put an excess of material where there is so little probability of its being needed, and where a failure would merely produce local damage.

THEORY OF FIRE PROTECTION

Mr. Spencer B. Newberry, in an address delivered before the Associated Expanded Metal Companies, Feb. 20, 1902,* gives the following explanation of the fire-proof qualities of Portland cement concrete:

The two principal sources from which cement concrete derives its capacity to resist fire and prevent its transference to steel are its *combined water and porosity.* Portland cement takes up in hardening a variable amount of water, depending on surrounding conditions. In a dense briquette of neat cement the combined water may reach 12%. A mixture of cement with three parts sand will take up water to the amount of about 18% of the cement contained. This water is chemically combined, and not given off at the boiling point. On heating, a part of the water goes off at about 500° Fahr., but the dehydration is not complete until 900° Fahr. is reached. This vaporization of water absorbs heat, and keeps the mass for a long time at comparatively low temperature. A steel beam or column embedded in concrete is thus cooled by the volatilization of water in the surrounding cement. The principle is the same as in the use of crystallized alum in the casings of fireproof safes; natural hydraulic cement is largely used in safes for the same purpose.

The porosity of concrete also offers great resistance to the passage of heat. Air is a poor conductor, and it is well known that an air space is a most efficient protection against conduction. Porous substances, such as asbestos, mineral wool, etc., are always used as heat-insulating material. For the same reason cinder concrete, being highly porous, is a much better non-conductor than a dense concrete made of sand and gravel or stone, and has the added advantage of lightness. In a fire the outside of the concrete may reach a high temperature, but the heat only slowly and imperfectly penetrates the mass, and reaches the steel so gradually that it is carried off by the metal as fast as it is supplied.

*Cement, May, 1902, p. 95.

TESTS OF FIRE RESISTANCE

Prof. Ira H. Woolson of Columbia University has made several series of tests* to determine the effect of heat upon the strength and elastic properties of the concrete and upon the thermal conductivity of the concrete and the imbedded steel.

Effect Upon Strength. Tests to determine the effect of heat treatment upon the strength and elastic properties of different mixtures showed that the trap concrete was least affected. Concrete two months old, in proportions 1:2:4, the crushing strength of which before heating was about 2500 pounds per square inch tested in 7-inch cubes, after being subjected to a heat of 1500° Fahr. for two hours gave a strength of about 1000 pounds per square inch. However, since this reduction in strength was due at least in part to the reduction in the effective area because of the surface deterioration (if the surface was injured to a depth of 1¼ inches the effective area would be reduced from 49 sq. in. to 20 sq. in.), it is probable that the interior of the blocks was affected very little. The concrete made with gravel, which in these tests was nearly pure quartz having a high coefficient of expansion, was affected to a much greater extent. Cinder concrete, which showed a normal crushing strength of about one-half that of the trap, after heat treatment gave a corresponding weakening.

The modulus of elasticity of the concrete was always greatly reduced by heat treatment.

CONDUCTIVITY OF CONCRETE AND IMBEDDED STEEL

As a result of the conductivity tests, which were made upon specimens of trap, gravel and cinder concrete having thermo-couples for measuring heat transmission imbedded so as to indicate the temperature at points varying from ½ inch to 6 inches from the heated face, Prof. Woolson drew the following conclusions:†

All concretes have a very low thermal conductivity, and herein lies their ability to resist fire.

When the surface of a mass of concrete is exposed for hours to a high heat, the temperature of the concrete one inch or less beneath the surface will be several hundred degrees below the outside.

A point 2 inches beneath the surface would stand an outside temperature of 1500° Fahrenheit for two hours, with a rise of only 500° to 700°, and points with three or more inches of protection would scarcely be heated above the boiling point of water.

* Proceedings of American Society for Testing Materials, Vol. V, 1905, p. 335; VI, 1906, p. 433; VII, 1907, p. 404.

† Proceedings American Society for Testing Materials, Vol. VII, 1907. p. 408.

The fact that cinder concrete showed a higher thermal conductivity than the stone concrete would indicate that its well-known fire-resistive qualities are due, in part at least, to the incombustible quality of the cinder itself.

The thermal conductivity of the gravel concrete* was fully as low as that of the trap, but the specimens of gravel concrete cracked and crumbled in many cases when the trap and cinder specimens under similar treatment remained firm and compact.

In the tests on the conductivity of imbedded steel with the end projecting from concrete, Prof. Woolson found practically the same results with concrete from all three aggregates. With the temperature of the end surface of the concrete and the projecting end of the bar 1700° Fahrenheit, a point in the bar only 2 inches from the heated face of the concrete developed a temperature of only 1000° Fahrenheit, while at a point 5 inches in the concrete the temperature was only 400° to 500°, and at 8 inches the temperature reached only the heat of boiling water.

From these results Prof. Woolson concludes that "where reinforcing metal is exposed in the progress of a fire, only so much of the metal as is actually bare to the fire is seriously affected by it."

Tests by the National Fire Protection Association† in 1905 upon beams 8 inches by 11¼ inches by 6 feet long, of different kinds of concrete, showed that the strength of rods imbedded 1 inch from the lower surface was reduced about 25 per cent after heating to a temperature of 2000° Fahrenheit for one hour. With rods imbedded 2 inches a similar reduction in strength occurred after 2 hours and 20 minutes heating, and the strength of the concrete was appreciably reduced to a depth of 4 inches from the sides and bottom.

The hardest and densest mixtures were usually the poorest conductors of heat; the cinder concrete gave, however, a slower rise of temperature than the others.

INFLUENCE OF CRACKS IN REINFORCED CONCRETE UPON THE CORROSION OF STEEL

It has been seriously questioned whether the minute cracks which open in a concrete beam and slab even under loads which are absolutely safe do not permit corrosion of the steel reinforcement. Tests by E. Probst‡ in

*As stated in connection with the tests on preceding page, this gravel was nearly pure quartz. In other tests, concrete with gravel containing a larger percent of slate or other similar mater al has given much better results.

† *Cement*, January, 1906, p. 273.

‡ Report of the Royal Department of Testing Materials in Gross Lichtenfelde, West Prussia.

Germany, in 1907, indicate very conclusively that steel in reinforced beams, laid in ordinary wet concrete used in practical construction, is in no danger of rusting through the cracks formed in the concrete under tension, until nearly the breaking point of the steel. The specimens, 34 beams, which contained both plain and deformed bars and rusted and unrusted steel, were subjected in loading to the action of a mixture of oxygen, carbon dioxide and steam, for a period of from 3 to 12 days. Unprotected steel subjected to this mixture was badly rusted in two hours. After breaking up the specimens of concrete no rust was found even on steel stressed to its elastic limit, although some was discovered on steel stressed nearly to its breaking point, which could be attributed to large cracks extending to the metal and uncovering it.

PROTECTING STRUCTURAL STEEL

In San Francisco at the time of the earthquake and fire, April, 1906, there were few concrete structures, but these stood the test of fire and shock on the whole better than any other material.*

Observations after the fire indicate that concrete is also an effective protection for steel frame construction, but that it preferably should be enclosed in a metal basket.

Captain John S. Sewell, Engineer Corps, U. S. A., in his report to the U. S. Government† suggests that when such a basket is used the total thickness of concrete upon the exposed flanges of girders and floor beams should be 2 to 3 inches according to circumstances. For columns incased in a metal basket or cage, a thickness of 3 to 4 inches was recommended.

The structural steel in the Boston subway,‡ imbedded for twelve years in concrete or protected by the cement mortar joints of brick arches, was found upon examination during changes in the structure to be free from rust. The only exception to this was under the rather large base plates (21 by 24 inches) of columns, where a thin layer of rust frequently was found, having tubercles sometimes ¼ inch thick. This was evidently due to the settling of the finer parts of the concrete under the plates. The small base-plates were practically free from rust.

* Transactions American Society Civil Engineers, Vol. LIX, 1907, p. 208.

†U. S. Geological Survey, Bulletin 324, 1907.

‡Personal correspondence with Mr. Howard A. Carson, Chief Engineer.