THESIS

FIRE TESTS ON CONCRETE

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Concrete - Testing

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FIRE TESTS ON CONCRETE

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"Concrete Engineers Handbook"

Hool and Johnson.

"Engineering"

Professor F. C. Lea.

"Fire Tests"

National Board of Fire Underwriters.

"Report on the Fire of the Edison Phonograph Works"

National Fire Protection Association.

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FIRE TESTS ON CONCRETE.

In maintaining this report, "Fire Tests on Concrete" it is the writers purpose to show both by experiments of their own and experiments carried on by the National Board of Fire Underwriters and other organizations, the effect of fire upon concrete, both plain and reinforced.

Plain and reinforced concrete structures are very common in these days, and buildings made of this material are frequently referred to as fire-proof. In the United States as well as in Europe and Canada, disastrous fires have, however, frequently proved that providing a fire rages for a considerable length of time, as is often the case in large warehouses, these structures fail badly and in many cases it has been necessary to dismantle the building completely.

By experiments of our own and experiments conducted by the Fire Underwriters and other organizations, we have been able to arrive at some very interesting and definite conclusions. It is our aim to show to just what extent concrete can be considered as fire-resisting. In this report will be considered the action and effect of fire upon plain and reinforced concrete; columns, walls, beams, slabs, and partions.

In considering the effect of fire upon reinforced concrete the problem can be stated under two headings:

1. Is it possible to make concrete which will retain its strength during and after exposure to high temperatures liable to occur in a building fire?
2. Is it possible to prevent the steel from reaching such a temperature that its strength is reduced to or below, that required to carry the load occurring in the same building?

Concrete essentially consists of fragments of stone held together by a net work of mortar. This mortar in itself is a fine aggregation consisting of fine grains of sand "stuck" together by Portland Cement. An examination of concrete shows one peculiarity very strikingly - it is porous. The Voids vary in size from those easily visible to the naked eye, to a mass of fine channels and cavities of microscopic dimensions.

The mode of failure of concrete may be as follows:

1. The concrete can be considered to consist of a network of cement holding together stones of various sizes; if the finer aggregation

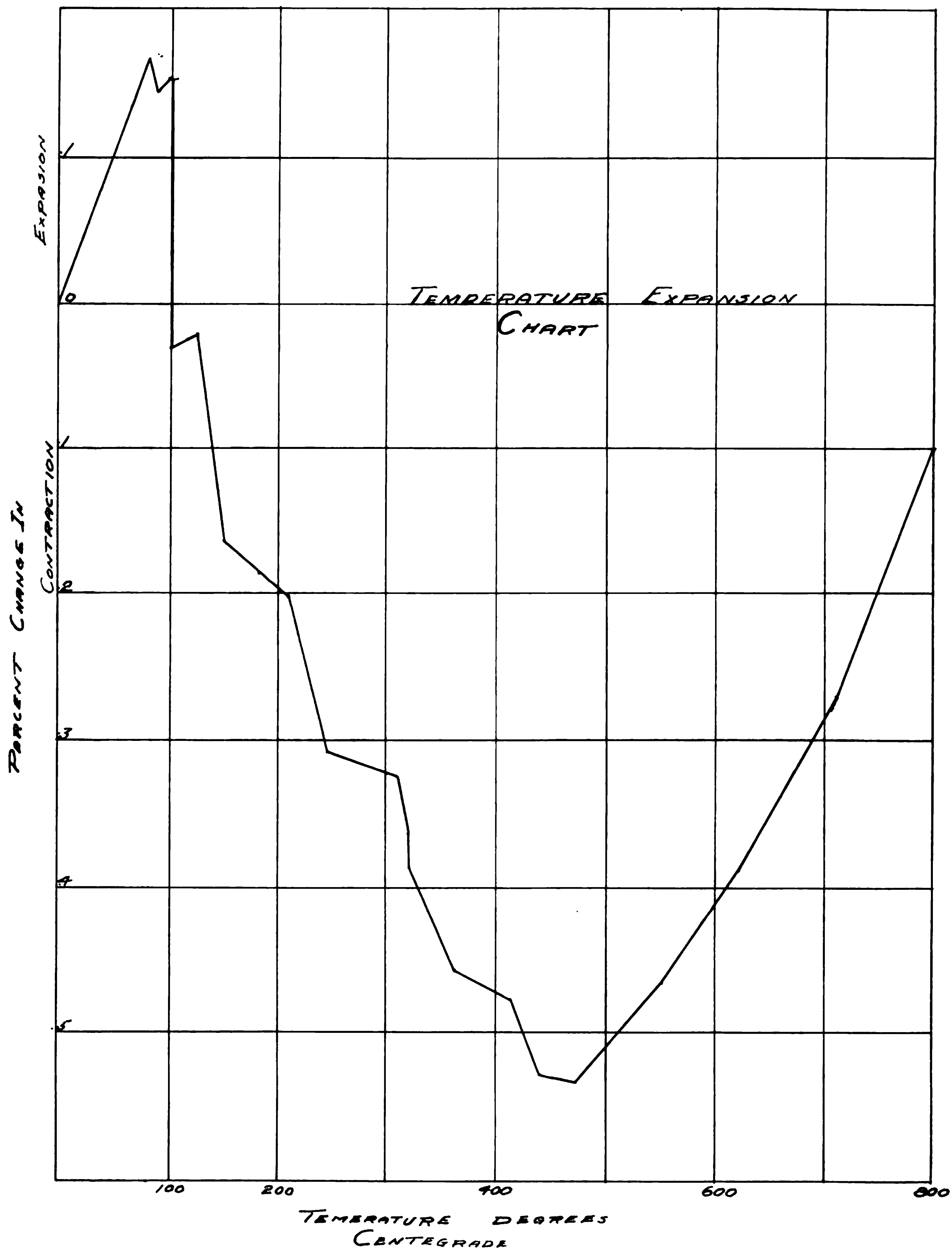
of mortar is caused to fail the whole mass will be disintegrated quite independently of any effect the coarse aggregate may have.

2. In such a network structure if all the stones are covered with cement no increase in total volume can take place unless the cement itself expands. When expansion takes place the stresses will be produced in the coating cement and in the aggregate, unless the expansion of the cement is exactly equal to that of the aggregate. These stresses may be sufficient to cause cracking of the cement, or when cooling takes place may lead to separation between adjacent boundaries.

This being the case concrete may fail in high temperatures due to the different coefficient of expansion of sand and cement or it may fail by the cement itself breaking down caused by some innate property of the cement, which would take place whether the sand were present or not.

The coefficient of expansion of quartz, which is the chief constituent of all sands used in practice

FIGURE 2.



TEMPERATURE EXPANSION
CHART
EXPANSION
PERCENT CHANGE IN
CONTRACTION
.1
0
.1
.2
.3
.4
.5
100
200
400
600
800
TEMPERATURE DEGREES
CENTEGRADE

has been fairly accurately determined and expands at a quit uniform rate.

Cement is entirely different. The results of a number of tests show that up to 100°C, cement has a fairly steady increase in expansion, but at 100°c, a very large contraction is started, this contraction continues until a temperature of 491°C, was reached. At this time the cement has contracted until it is much smaller than its original size. After 491°C is passed expansion commences, and takes place at a rate less than that occurring during the expansion previous to 100°C.

Figure (1) gives a graph showing the relation between temperature and expansion of cement.

Another thing to take into consideration is the effect of heat on hydrated and hardened portland cement. It was found that water was given off at a fairly fast rate up to 110°C. From there on water continued to be given off but not as rapidly as before.

There can be little doubt that the contraction obtained in the experiments and described above, as designated to ascertain the value of the coefficient of expansion, is due to this dissociation of water from the hydrated cement.

Fig 1.

Photo-micrograph magnified 100 diameters.

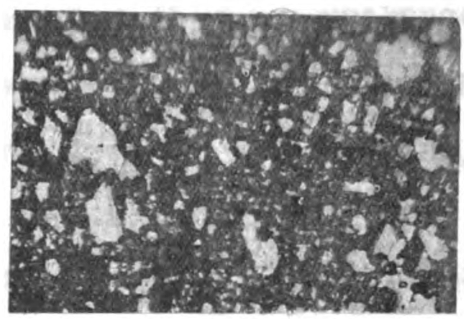


Figure 2 is a photo-micrograph of a sample of set concrete which has been magnified 100 diameters. The method of etching causes the softer portions (dark in the picture) to be rubbed away and leave the harder (white in the picture) standing out from the surface. By further examination of these harder portions, it can be shown that they are unchanged particles of Portland cement clinker, that is, grains which have never been hydrated by the mixing of the concrete. In this case we really have hydrated cement surrounding particles of inert and unchanged clinker, the presence of which is partially due to the coarseness of grinding. Though these particles are fine enough to pass a 180 x 180 standard seive. As the temperature rises more expansion of the unhydrated fragments will take place causing hydrated cement to break down.

This action will continue until all the unchanged clinker is free to move and expand when the specimen on further heating may expand or contract, depending upon the relative movements of the hydrated and unchanged portions.

From extensive experiments carried on in England we learn that when concrete is raised above 100° C, then contraction will occur. On the other hand steel imbedded in the concrete will continue to expand as the temperature rises. When this happens the adhesion between the steel and concrete must break down either by a complete sliding of the steel through the concrete or the concrete must crack and leave the steel in this manner. In practice it is usually the latter which occurs.

With the amount of concrete covering ordinarily allowed in design it is somewhat doubtful whether the question of heat conductivity of the concrete is of primary importance. This spalling action will, in many cases, occur long before the temperature of the steel can have risen to the degree which is dangerous. This spalling is caused by the sudden and intense heat which produces a rapid expansion of the concrete near the surface of the column at right angles to each other, subjecting each corner to stress from two directions tending to force the corner off in the line of the diagonal. At the same time the surface concrete, especially at the corners where heated on two faces tended to expand lengthwise and thereby assume an undue proportion of the column load with the result that shearing stresses are produced between the highly heated corners and the colder interior portions of the column. This action occasioned a buckling effect of the concrete at right angles to the length of the column.

The combination of these forces will produce tensile and shearing stresses in the diagonal planes across the corners, which results in splitting them off lengthwise. This spalling action will be seen to be the most serious at the underside of beams and the sides of columns. If a concrete that will not spall can be discovered the conductivity will be the only, and not by any means the most serious menace.

These experiments were performed within a few hours after the speciman had been taken from the fire. But by accident one piece was not tested for over a week. It was found to have lost strength quite out of proportion to the amount of heating. When a block was taken from the furnace no cracks on the surface were noticed but when exposed to the atmosphere of the laboratory, numerous cracks occur and the block may even crumble.

The explanation of this phenomenon can be found in the fact that one of the chief products of hydration of Portland cement is calcuim hydrate. This dissociates into quick lime and water at about 400°C.

$$Ca\ (OH)_2 \rightleftharpoons CaO + H_2O$$

It must be realised that this is accompanied by a contraction of the concrete. Concrete is porous and the air getting in will carry moisture with it. This moisture will hydrate the quick lime again and the product of hydration ($Ca(OH)_2$) occupies a considerably greater volume and hence causes the concrete to crack, split, and ultimately crumble.

The importance of this "after effect of fire" cannot be over estimated. When the question has to be faced as to whether the building is afterwards safe, and if not, how much of it should be demolished and rebuilt, and the answer would appear to be not very encouraging.

In view of the large number of buildings already erected of reinforced concrete, the problem cannot safely be left at this point, but in the opinion of the writers the next work should be done on full sized structures that have undergone these conditions.

In view of this fact we will first consider columns. While columns form the most important element in the strength of a building, few representive tests have been made to determine their ability to support load when exposed to fire. The purpose of the following experiments, run by the National Board of Underwriters, on full sized columns, was to ascertain:

1. The ultimate resistance against fire of protected and unprotected columns as used in the

interior of buildings.

2. Their resistance against impact and sudden cooling from hose streams when in a highly heated condition.

The fire test series includes:-

1. Tests of representive types of unprotected structural steel, cast iron, concrete-filled pipe, and timber columns;
2. Tests where in the metal was partly protected by filling the reentrant portions or interior of columns with concrete;
3. Tests wherein the load carrying elements of the column were protected by a 2 inch or 4 inch thickness of concrete, hollow clay tile, clay brick, gypsum block, and also single or double layer of metal lathe and plaster;
4. Reinforced concrete columns with 2 inch integral concrete protection

Although our chief interest is in the effect pf fire upon concrete these other tests will give a fair and just comparison and at the same time show the advantages or disadvantages of concrete against some of the other materials. At the same time the full action of the fire tests upon the concrete will be shown.

The test columns were designed for a working load of approximately 100,000 lbs., as calculated according to accepted formulas. The load was maintained constant on the column during the test, the efficiency of the column or its covering being determined by the length of time it withstood the combined load and fire exposure.

The latter was produced by placing the column in the chamber of a gas fired furnace whose temperature rise was regulated to conform with a predetermined time-temperature relation. Measurements were taken of the temperature of the furnace and test column and of the deformation of the latter due to the load and heat.

In the fire and water tests the column was loaded and exposed to fire for a predetermined time, at the end of which the furnace doors were opened and a hose stream applied to the heated column, the duration of the application and pressure at the nozzle varying with the length of time the corresponding type of column withstood the regular fire tests.

All columns tested were of 12 ft. 6 inch effective length with an additional 3 ft. to take up the load and transmit it to the columns. As our chief interest lies in the concrete columns it will suffice to say that

the other columns tested were all determined as to size and loading by well known formulas and a comparison made between the final results of the concrete protected columns against those not protected. We will discuss the columns in the following manner:

A. Columns Protected by Concrete.

Under this test Rolled H, 2-bar and plate, plate and angle, plate and channel, latticed channel, I-beam and channel, starred angle, latticed angle, round cast iron, columns were used protected by Concrete 2 inches to 4 inches thick. Six combinations of fine and coarse concrete aggregates, as used in building construction in four large industrial centers, were used; namely:-

1. Rochport granite with Plum Island sand for Boston, Massachusetts district;
2. Chicago limestone with Fox River sand, and Joliet gravel with Joliet sand for the Chicago district;
3. Cleveland sandstone with Pelee Island sand for Cleveland, Ohio, district;
4. New York trap rock with Long Island sand, and hard coal cinders with Long Island sand for the New York, N. Y. district. Portland cement was used throughout the tests.

The proportions of the mixture used were 1:2:4 and 1:3:5 for the stone and gravel concrete and for the cinder concrete 1;1½;4½ and 1;2:5. The cinders were used unscreened except that pieces larger than 1 inch were crushed to smaller size.

Ties consisting of No. 5 (B.& S. gauge) bright basic steel wires were wound spirally around the structural section on vertical pitch of 8 inches.

The porportioning of aggregates were based on volume parts of the materials except that the Portland cement was measured in the original package. The sand and stone were measured in deep steep wheel-barrows, the volume of each being determined by a templet of the required shape. All concrete was mixed in a motor driven concrete mixer. Everything was conducted as nearly as possible to the actual field work.

The sand and coarse aggregate was all tested according to the required tests for each, and was then porportioned in the right amount for the different mixes. The concrete specimens were cylinders 8 inches by 16 inches. These cylinders were tested, for each column, in the usual manner. The loading apparatus was a special hydro-pnemmatic ram which was designed to maintain a constant load during the test. The columns were moved to their place in the furnace by a carriage built especially

for this purpose. The furnace was heated by means of four primary blast burners arranged to discharge in an inclined direction upward and toward the adjacent corner. The burners are supplied with gas. All temperature measurements were made by the thermo-electric method.

The columns were measured for three kinds of deformation:

1. The unit compression and expansion over a definite gauge length,
2. The total depression or expansion of the column measured at a point above its heated portion.
3. The lateral center deflection.

In case the column withstood the 8 hour fire test it was immediately loaded to failure under full fire exposure.

In the fire and water test series, the protected structural steel, the two unprotected cast, and the three reinforced concrete columns were loaded to failure after they had cooled.

The duration of the fire periods varied from 22½ minutes to 1 hour, and that of the subsequent water application, from 1 to 5 minutes. The length of the maximum fire period was determined by the time within which water is generally applied in building fires, which is estimated at one hour.

In applying the hose stream, the nozzle was moved back and forth on one side of the furnace and maintained at a constant distance from the column, the water being applied in succession over the full height on three sides.

B. Reinforced concrete columns.

Tests were run on three kinds of columns:

1. Square vertically reinforced,
2. Round vertically reinforced,
3. Round hooped reinforced.

They were all made of a 1:2:4 mix and the material, apparatus, and manner of testing was the same as in the preceeding Section A.

It appears from the tests of concrete applied as a protective covering or filling to steel or cast iron columns, that the concrete retards the temperature rise in the metal when the column is exposed to fire and further retards the failure by carrying portions of the column load proportionate to its relative area and rigidity as compared with the metal.

The protections were applied as square or round coverings, generally 2 inch and 4 inch in thickness, measured from the surface of the covering to the metal. The time of failure in the fire tests, varied from 1 hour, 47 minutes, to 7 hours, 57 minutes

for the 2 inch protections, and from 3 hours, 47 minutes to over 8 hours for the 4 inch protections.

No evidence was developed that variation in the strength of the concrete of the same aggregate and porportion of mixture had any appreciable influence on the results of fire tests of concfete protections. This was due to the large change in mechanical properties produced by the heat. Concrete as made with different aggregates preserves strength to different degrees on exposure to fire.

With a given thickness or size of covering the main cause of variation in results was the difference in fire resisting properties of concrete made with different aggregates. In this particular the concrete can be placed in three groups: That giving the most unfavorable results was the concrete made with Merimec River sand and gravel. This was due to the fact that this sand and gravel consisted almost wholly of quartz and chert grains and pebbles, the gravel having a particularly high chert content. Both minerals are found in silica ($Si\ O_2$), the quartz being crystalline and unhydrous, and the chert amorphous with a variable amount of water in chemical combination. On being heated part of the combined water in chert is liberated and the consequent vaporization disrupts the pebbles. Other causes of disruption of concrete made with silioeous aggregates are abrupt volumn changes. The columns made of this gravel with a high silica content gave for the covered reinforced concrete, from one hour fire resistance to two and one half hour fire resistance depending on the thickness of covering. The reinforced columns also showed that this kind of aggregate was very poor and only gave a five hour fire resistance teot.

The middle group includes concrete made with trap rock, granite, sandstone and hard coal cinder.

In tests with trap rock and cinder concrete a small amount of cracking occurred and during the last part of the fire period, no spalling of any note occurred before failure. In the granite concrete cracks developed earlier in the test and spalling took place during the last 30 minutes of the test period. In the test of the sandstone concrete, cracking and spalling began in the first 30 minutes and continued for an hour, after which there was little apparent change before failure.

Fusion of the trap rock concrete occurred where the test extended beyond seven hours, the concrete being affected to a depth of about 1½ inches. Flowing of concrete due to fusion, while not general, occasionally formed pockets up to 2 inches in depth.

The third group comprises protections of Chicago limestone concrete, and Joliet gravel concrete.

The composition of this gravel is similar to that of Chicago limestone and the tests compare quite closely. Very little cracking resulted on exposure to fire and their heat insulating value was increased by the change of the calcium and magnesium carbonate to the corresponding oxides. This process retarded the flow of heat through the region of change and left material of good insulating qualities. Immediately after test the surface of the concrete was firm, but after a few weeks exposure the hydration of the oxides caused slacking and crumbling of the calcined material.

From a comparison of the thickness of protections it shows that a four inch protection is much better than a two inch protection, although there was only a difference of a few hours and the good two inch coverings all withstood the 8 hour test.

Concrete as made with different aggregates preserves strength to different degrees on exposure to fire. This had a decided influence on results, the longer test periods and particularly the longer intervals between maximum expansion and failure of the limestone concrete and Joliet gravel concrete can be attributed in a great part to this cause.

There seems to be little difference as to the shape of concrete, coverings or columns, as concrete

made with a highly siliceous composition makes the other defects small in comparison to that of the aggregate.

In covered structural steel columns it is much better to have a wire netting around the column as it tends to hold the concrete to the steel. In the case of the water tests the covering was carried away from the unprotected columns while those where wire was used the concrete held fairly well.

In regard to the reinforced concrete columns the experiments show the following results:

The limestone concrete columns all withstood the 8 hour fire test and while hot sustained loads exceeding twice the load applied in the 8 hour period. The two vertically reinforced trap rock columns failed after 7 hours, 23 minutes, and 7 hours, 57 minutes, respectively, and the hooped column withstood the 8 hour fire test and failed under a load about 25 percent greater than the load sustained during the fire test. A 2 inch thickness of concrete next to the surface was assumed as covering in all cases and not included in the area used in computing working loads. The difference in results within the group can be attributed to concrete aggregate, the other incidental factors being comparable to, or favoring the tests giving the lower results. The trap rock concrete fused and fluxed at some points to a depth of one inch, which undoubtedly affected the time of failure to some extent. The results obtained with the concrete of both aggregates show a high degree of fire resistance.

No effects due to shape of column or form of reinforcement were evident, differences in results being within the limits of incidental variations in test columns and conditions. No line of cleavage outside of the wire reinforcement was found after test in the hooped column of limestone concrete, except in the immediate region of failure, where it was apparently induced by the strains that developed when the column failed. In the case of the corresponding trap rock concrete column, more evidence indicating separation of the outer protection from the core at the line of the reinforcement was found, effects in part which may have been caused by the fire exposure.

One length of the hooped reinforced concrete columns about three feet long was cut outside of the failure region in the fire test and subsequently tested in compression. The limestone concrete specimen sustained a total load of 517,000 lbs., as against 243,000 lbs., immediately following the fire test, and the trap rock concrete specimen, 342,000 lb. compared with 163,000 lbs., at the end of the fire test. The greater part of this variation in strength can be attributed to recovery in strength of concrete and reinforcement.

The concrete of the columns subjected to fire and water tests was placed in three sections to permit using two or three kinds in each column.

In the case of the square vertically reinforced column, the water carried away the concrete at the corners outside of the bars and pitted the concrete on the most exposed face to depths of from 1/8 inch to 1 inch for the limestone concrete and to a depth of 2 inches for the Meramec River gravel concrete.

In the round vertically reinforced column, the limestone concrete was pitted to a depth of 1 inch and some of the concrete in the upper portion of the Joliet gravel concrete section was carried away. That consisting of Meramec River gravel concrete, the outer concrete was stripped off by the water, exposing the reinforcing bars on two sides. In this as in the preceeding large cracks had formed in the concrete during the fire period.

In the fire and water test of the hooped reinforced concrete column, the water stripped the Merimec River gravel concrete and the granite concrete

FIGURE 3.

Note the concrete hanging fron the under side of the girder in small stalactiyes.

from the wire reinforcement on three sides during the first 15 seconds of the water period. Spalling of the concrete had exposed portions of the reinforcement during the fire tests. Further application of water caused stripping to the reinforcement in the upper section of trap rock concrete and increased the effects in the lower sections.

From all of these experiments a great many things are determined but each large fire brings some new unforseen thing to ones attention. Perhaps one of the worst fires occurring in a concrete building was that which destroyed the "Edison Phonograph Works" in West Orange, New Jersey, in 1914.

Perhaps one of the most interesting things learned from this fire was the fusing of concrete in the basement of the Wax house. The ceiling, beams, girders, and columns supporting them in this lowest story show remarkable appearance of fused concrete (see figure). Small stalactites of concrete slag hang down from the ceiling and large bunches of it achere to the columns where it has run down and hardened. The lower part of these three beams has wasted away, exposing the reinforcement which has melted or burned out, causing failure of the beam. The under side of the floor slab adjoining these beams has also wasted away, exposing the metal reinforcement parts of which has melted and hangs down in tapering rods, the area of which has been reduced in some cases to about one eighth of its original size. The columns, in addition to being fused on the surface, have also spalled. This would indicate a temperature of 2500°F, or more at this location.

The action of the columns was not as satisfactory as that of the other concrete members. Most of the columns were square and reinforced by twisted bars located at the four corners two to four inches from the surface. The sudden and intense heat produced rapid expansion of the surface concrete, resulting in severe internal stresses.

The corner reinforcement bars also tended to produce a plane of weakness in the concrete, many of the corners splitting off along the line of these two bars. In some cases the bars may have expanded sufficiently to have aided the splitting action, but the indications are that most of these corner failures originally occurred outside of the bars, at a point where the stresses more than equalled the tensile strength of the concrete in the diagonal plane of failure. With the corners removed, the reinforcing bars had little protection from the heat, consequently expanded rapidly forcing themselves out of the columns, and carrying with them any attached surface concrete. The coefficient of expansion of the concrete is approximately the same as for steel, and as all the heat reaching the steel bars would have to pass through the concrete covering, it is probable that the former would always be a little cooler than the latter. This assumption is strengthened by the fact that one side of each bar was in contact with the cool interior concrete. Furthermore the thumal conductivity of concrete is low.

In spite of the disintegration of the surface concrete, it is probable that if the bars had been properly tied, many of them would have stayed in place and the column injuries would have been less severe.

In most cases it was the wall columns that failed. The greater injury to wall columns is believed to be due to two causes. First, to the fact that while subjected to intense heat on the room side, the opposite side exposed to the outer air was kept comparatively cool, and was in some cases subjected to cold water, from hose streams; Second, owing to the columns being held rigidly in position vertically from the floor to the top of the panel walls, they were less able to resist the expansion of the building as a whole, which naturally resulted from the attack of fire. It is probable that reinforced, and that they were free to bend from floor to ceiling in the direction in which the building expanded. This theory of the bending of the column due to the expansion of the building is further substantiated by the existence in all cases of a V-shaped crack between the corner column and the adjacent wall panel, starting at the floor and widening upward.

While these various theories and descriptions may explain what actually happened in the sequence of events preceeding the failure of different structural parts of these buildings, they do not justify the general conditions which produced the results which confront us, and unless the experience thus gained will insure that future specifications shall be drafted to prevent a repetition of such a disaster under similar conditions, it will indicate that either the lesson has not been properly learned, or that the design and construction of these buildings is not suited for the purpose employed. Whether any other system of construction would have given better results under the same conditions, is problematical. The lesson is being carefully studied by many competent persons. The knowledge gained, will doubtless aid in eliminating unwise practices in reinforced concrete construction. It has needed an expensive lesson of this kind to demonstrate the strict necessity for changes in design, and methods of construction to meet such conditions. Reinforced concrete buildings can doubtless be built which would withstand such a fire satisfactorily, but no type of construction should be left to meet such an attack without the assistance of any of the standard fire resistive measures which should be a part of every first class building.

It appears from an examination of these tests that structural steel columns protected by 2 inches of concrete withstood the fire tests from 1 hour, 45 minutes, to 7 hours, 57 minutes. Structural steel columns protected by 4 inches of concrete withstood the fire tests from 3 hours, 40 minutes, to 8 hours, 30 minutes, and these required an additional load before failure occurred. Reinforced concrete columns withstood the fire tests from 7 hours, 25 minutes, to 9 hours, these failed under an additional load. The other forms of columns did not reach any such limits - most of them failing under a 5 hour fire tests.

Hence, it can be said that with a proper aggregate, good reinforcing, and everything carried on in the proper way, concrete affords very good fire protection and unless an unusually large and furious fire occurs there is no better fire resisting substance than concrete.

The purpose of our experiments is to ascertain to what extent fire will effect concrete. To do this we used material purchased on the retail market so that we could perform our experiments with material as nearly like that used in regular construction as possible. We also wished to determine the difference in effect, if any, upon cement manufactured from marl and that manufactured from limestone.

The materials used were those that were purchased in Lansing, Michigan, The cement used was known by the trade name of New Aetna (a marl cement) and Petoskey cement (a limestone cement). The coarse aggregate was washed Mount Hope gravel. This gravel is secured from the Mount Hope gravel pit just outside of Lansing, and is the same as that used in the construction of four large buildings on the Michigan Agricultural College Campus at the present time. Standard Ottawa sand was also used.

The tests were run in three series, namely, tests on briquettes, cylinders and beams.

BRIQUETTES.

The normal consistency of the cement was first found by the Vicat needle consistency test. This test was repeated four times and an average taken. The consistency of the Petoskey cement was found to be 27, and that of New Aetna, 27.25. The briquettes were made as recommended by Hool and Johnson, a standard method.

The cement is mixed for 1.5 minutes and then pressed into the moulds firmly with the thumbs and smoothed with a trowel. The briquettes were tested on a standard testing machine in the cement laboratory of the Michigan Agricultural College.

THOSE MADE FROM MARL CEMENT.

NEAT CEMENT.

10 - tested after being subjected to fire,

10 - before being subjected to fire,

1 - 3 Standard sand.

10 - tested after being subjected to fire,

10 - tested before being subjected to fire.

THOSE MADE FROM LIMESTONE CEMENT.

NEAT CEMENT.

10 - tested before being subjected to fire,

10 - tested after being subjected to fire.

1 - 3 Standard Sand.

10 - tested before being subjected to fire,

10 - tested after being subjected to fire.

These samples were placed in water after 20 hours and remained there for 24 days, at which time they were taken from the water and allowed to dry for 6 days before testing.

CYLINDERS.

The cylinders were made of the above mentioned gravel and were of a 1 - 2 - 4 mix. They were 6 inches in diameter and 12 inches high. The forms were removed after 24 hours and the specimen allowed to stand in the air for 27 days. They were tested for compression only on a Standard compression machine in the Strength of Materials Laboratory at the Michigan Agricultural College.

MADE OF MARL CEMENT.

4 - tested before being subjected to fire,

4 - tested after being subjected to fire.

MADE FROM LIMESTONE CEMENT.

4 - tested before being subjected to fire,

4 - tested after being subjected to fire.

BEAMS.

The beams were made of the same material and mix as the cylinders were made of. They were limited in size by the furnace in which they were to be heated. Four specimens were made, two being of marl cement and two of limestone cement. These beams were tested on Standard testing machines in the Strength of Materials Laboratory of the Michigan Agricultural College.

DESIGN OF BEAM.

Assume 2000 lb. concrete.

$$f_s = 32000 \text{ lbs.}$$

$$\frac{f_s}{f_c} = \frac{32000}{2000} = 16$$

$$K = \frac{1}{1 + 16} = .652$$

$$J = 1 - 3/8 \times .652 = .755$$

$$P = 2/3 \times \frac{.652}{16} = .0272$$

$$W = 80{,}000 \text{ lbs.}$$

$$M = \frac{W}{2} \times \frac{l}{2} = \frac{80000 \times 20}{4} = 400000 \text{ in. lbs.}$$

$$bd^2 = \frac{400000}{2/3 \times 2000 \times .652 \times .755} = 609$$

$$d^3 = 609 \times 1.6$$

$$d = 9.9''$$

Say 10 inches,

$$b = 5/8 \times 10 = 6 \text{ inches,}$$

$$D = 11\ 1/2 \text{ inches,}$$

$$A_s = 6 \times 10 \times .0272 = 1.63$$

$$V = \frac{400000}{6 \times .755 \times 10} = 884$$

2 - one inch reinforcing bars are used.

Web reinforcing is needed, therefore 3/8 inch steel is used, placed vertically every two inches throughout the length of the beam. The beam was designed to be broken this necessitating the large value for f_s.

TESTS MADE ON BRIQUETTES.

Petoskey		New Aetna	
Neat	Ottawa Sand	Neat	Ottawa sand.
280	360	180	195
185	315	185	235
180	190	230	180
230	325	235	250
360	220	305	165
240	345	160	255
220	260	330	310
360	285	325	180
295	295	200	250
325	285	200	245
278 lbs. per sq. in. average	278 lbs. per sq. in. average	235 lbs. per sq. in. average	227 lbs. per sq. in. average.

TESTS MADE ON CYLINDERS BEFORE FIRING.

PETOSKEY	NEW AETNA
39,4000	48,000
42,600	42,400
43,800	41,800
46,900	44,300
43,175 average =	44,125 average =
1542 lbs per sq. in.	1576 lbs. per sq. in.

TESTS MADE on REINFORCED CONCRETE BEAMS.

The beams that were not subjected to the fire test were loaded to failure in the Strength of Materials Labratory. They were found to fail by shear as our computations show. In both cases it was the concrete which failed and not the steel. The beams which were subjected to the fire test failed under very little load and when allowed to stand in the air for a few days all crumbled up and fell to pieces.

RESULTS of TESTS.

Beam made with Petoskey cement.

Failed at 26570 lbs.

Beam made with New Aetena cement.

Failed at 25980 lbs.

The fire tests were conducted in the heat treatment laboratory of the Michigan Agricultural College. The furnace used was a large anealing furnace and an accurate means of recording the temperature by means of an electric thermo couple was used.

The eight cylinders and fourty briquettes were placed in the same furnace at the same time. It took 45 minutes to raise the temperature of the furnace from 60° F, to 1600° F, at which temperature it was kept for two hours. The specimens were then allowed to cool slowly and after a period of 24 hours were removed from the furnace.

After a period of twenty minutes from the starting of the furnace cracks began to develop in the briquettes. Upon examination after the fire the briquettes were found to be very badly cracked. Some of the cracks extending through the specimen. These briquettes could stand no load and would crumble in the hands. They were also warped out of shape.

The cylinders were cracked but not as badly as the briquettes. When they were lifted by the hands the edges broke off and crumbled, and when tested by the machine would not stand 1 1/2 lbs. per square inch. In some of the cylinders the concrete appeared to be fused on the surface. This was evident by the masses of material which had started to run down the sides.

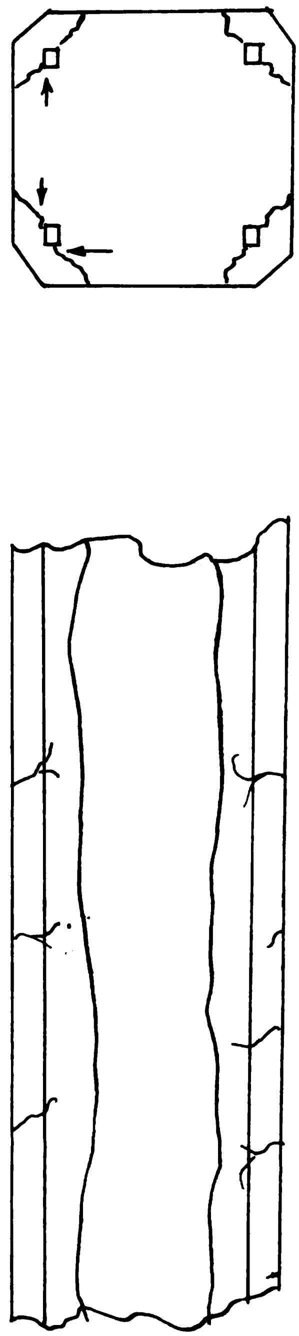
The reinforced beams were heated in the same furnace at a temperature of 1600°F, for two hours. The beams appeared to be as badly cracked as the cylinders and upon being removed from the furnace the edges crumbled not being able to support its own weight.

Concrete cylinder five days after firing.

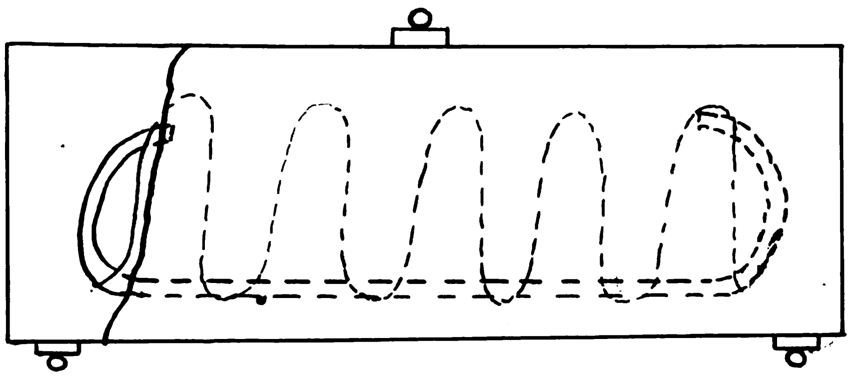
Concrete cylinder and beam five days after

firing.

Concrete beam as it looked five days after the fire, note the reinforcing iron.



SPALLING



SKETCH SHOWING REINFORCING

STEEL and FRACTURE

CONCLUSIONS.

Our very limited number of tests lead us to draw the following conclusions.

Concrete is far from being fire proof although to a large extent it is fire resisting. As far as we were able to determine there is no difference in the effect of fire on cement made from Marl and that made from limestone. In all of our tests it was the cement mortor rather than the aggregate that caused the concrete to fail. This is due to the hydration of the cement which occurs at about 400°C, dissociating the cement into quick lime and water. The water is then evaporated and leaves the cement to crack and ultimately crumble. On two of the fired cylinders there was evidence of a slight fusion of the aggregate but in all cases the aggregate proved to be stronger than the mortor. The concrete seemed to be sufficiently strong enough during the firing but it is the after effect of the fire that causes the most damage.

The importance of this "after effect of fire" cannot be over estimated. Even although it might be possible to make a concrete which will stand its full load at the time of the conflagration, yet when the question has to be faced as to whether the building is afterwards safe, and if not, how much of it should be demolished and rebuilt, the answer would appear to be not very encouraging.

In view of the very large number of buildings already erected in reinforced concrete, the problem cannot safely be left at this point, but in the opinion of the writers the next work should be done on full sized specimens. The form of answer for practical conditions of work depends upon one or two further factors which cannot satisfactorily be reproduced under laboratory conditions of the ordinary type.

As far as the present results are concerned, it is submitted that reinforced concrete as at present carried out in practice is anything bpt fire proof and the temperature of primary importance is a comparatively low one, probably about 400°C, this being the approximate temperature of the dissociation of calcium hydrate.

But as important a point as the resistance during fire is that of the after effects. It is suggested that extremely careful and very skillful examination of reinforced concrete structures after a fire, is required, and it is highly probably that the original factor of safety can never be replaced in the building structure except by complete reconstruction.