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FIRE RESISTANCE OF CONCRETE COLUMNS

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By W. A. Hull and S. H. Ingberg

ABSTRACT

Fire tests were made of 62 columns under working load, and 16 comparable columns were tested to failure in compression without fire test. The thickness of concrete or other material considered as protection was $1\frac{1}{2}$ or $2\frac{1}{2}$ inches. Concrete aggregates of a wide range in mineral composition were introduced.

The columns were subjected under normal working load to fire exposure increasing in intensity according to a predetermined time-temperature relation until failure or until the end of four hours, when additional load was applied up to the limit of the furnace equipment (600,000 pounds).

A wide difference in fire effects on different columns was noted and was determined as due in large part to difference in mineral composition of the concrete aggregates used. Quartz, chert, or granite induce spalling and cracking of the concrete when subjected to fire, while that made with calcareous aggregates, such as limestone or calcareous gravel, shows little visible effects even from very severe fires. As made with trap rock or blast-furnace slag, the fire effects are intermediate between those above indicated. Shape of section or type of column reinforcement were shown to be of minor importance. It was further shown that with concrete protection of siliceous aggregates or of plaster subject to cracking and spalling a large improvement can be effected by placing metal ties, such as wire mesh, in the protection. Columns made with siliceous aggregates and thus protected withstood under working load fires of four hours duration and at their conclusion in the heated condition loads from two to over four times the working load.

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I. INTRODUCTION

This investigation covers one phase of the work of the Bureau of Standards in the investigation of the fire-resistive properties of building materials and the fire resistance of various types of structural units, the study of fire resistance being, in turn, a part of a general program of investigation to provide information of use in the elimination of economic waste. The study of the fire resistance of concrete columns was made at the former Pittsburgh laboratories to supplement the investigation¹ which was conducted jointly at Underwriters' Laboratories, Chicago, Ill., by the Associated Factory Mutual Fire Insurance Companies, The National Board of Fire Underwriters, and the Bureau of Standards. The Chicago column tests included only a few concrete columns, and it was considered necessary to carry out a more comprehensive investigation which would establish, if possible, the fire resistance of the important types of columns built of concrete made from the principal types of aggregates.

A series of tests was accordingly outlined and conducted at the former Pittsburgh testing station of the Bureau of Standards during the period 1917 to 1919. Acknowledgments are due to C. W. Waidner, late chief of the division of heat and thermometry, and to P. H. Bates, in charge of the Pittsburgh branch at the time,

¹ Fire Test of Building Columns. B. S. Tech. Paper, No. 184.

for valuable suggestions and aid. Acknowledgments are also due to a number of other members of the staff for assistance on various portions of the investigation.

II. SCOPE OF THE INVESTIGATION

1. COLUMNS INCLUDING TWO CONTRASTING AGGREGATES

In the first part of the investigation only two aggregates were included. It had been found, in the course of a preliminary investigation² in which fire tests were made on small concrete cylinders 8 by 16 inches—made from a number of different aggregates, that those from siliceous gravel retained the least strength of all after the test, and those from limestone retained the most. Aggregates representing these two types were accordingly selected for that part of the work in which different types of columns with different kinds of reinforcement were to be compared. It was assumed that the behavior of a column of a given type would depend, in part, on the type of aggregate in the column, and, on the other hand, the performance of a column made from a given aggregate would depend, in part, on the shape of the column and the type of reinforcement in it, and it was considered desirable to determine the relations between types of columns and types of aggregates in their effect on the performance of columns under fire conditions.

From one gravel aggregate columns were made of the following types:

- (a) Columns 18 inches in diameter with 1 per cent spiral and 2 per cent vertical reinforcement.
- (b) Columns 18 inches in diameter with 2 per cent vertical reinforcement and no spiral reinforcement.
- (c) Columns 18 inches in diameter with no reinforcement.
- (d) Columns 16 inches square with 2 per cent vertical reinforcement.
- (e) Columns 12 inches in diameter with 1 per cent spiral and 2 per cent vertical reinforcement.

From a limestone aggregate the following types were made:

- (a) Columns 18 inches in diameter with 1 per cent spiral and 2 per cent vertical reinforcement.
- (b) Columns 18 inches in diameter with 2 per cent vertical and no spiral reinforcement.
- (c) Columns 16 inches square with 2 per cent vertical reinforcement.

² A Comparison of the Heat-Insulating Properties of Some of the Materials Used in Fire-Resistive Construction. B. S. Tech. Paper, No. 130.

All these columns, with the exception of the plain concrete ones, had $1\frac{1}{2}$ inches of protective concrete over the steel. In the plain concrete columns the outer $1\frac{1}{2}$ inches were regarded as protective concrete and the effective area of the columns calculated accordingly.

2. COLUMNS MADE WITH ADDITIONAL AGGREGATES

It was found early in the progress of the work that the gravel concrete columns had a decided tendency to spall, and that this tendency did not manifest itself at all in the limestone concrete columns. Spalling, by causing the loss of a large part of the protective covering, resulted in the attainment of comparatively high temperatures in the interior of the columns from which it occurred. It was found that there was a much stronger tendency for columns with spiral steel to lose their protective concrete by spalling than for round columns with vertical reinforcement only. Square columns made with siliceous aggregates also spalled freely. No spalling took place in limestone concrete columns of any kind. Since the characteristic tendencies of these two aggregates were shown in much stronger contrast in round columns with hooping and in square columns than in round columns without hooping, no round columns without hooping were included in the latter part of the investigation. With the evidence of the early tests in mind, columns from the following aggregates were added to the program:

- (a) Trap rock.
- (b) Blast-furnace slag.
- (c) Pure quartz gravel from Long Island.
- (d) A mixed gravel from Long Island, known as the Cow Bay gravel.
- (e) A calcareous gravel from banks near Elgin, Ill.

All these aggregates were tested in round columns 18 inches in diameter with both spiral and vertical reinforcement. In addition, one of the aggregates was tested in round columns with vertical reinforcement only and two of them in square columns with vertical reinforcement only.

3. CONCRETE COLUMNS WITH DIFFERENT KINDS OF PROTECTIVE COVERINGS

The evidence produced by the columns from Pittsburgh gravel, protected in the usual way—that is, with concrete outside of the steel—showed that columns from aggregates of this type could

not be considered as safe against fire as columns from a number of other common types of aggregates. Highly siliceous gravel is so widely distributed and so extensively used in concrete fire-resistive construction that the matter of its safety under fire conditions is of great importance. Consequently, it was considered proper to undertake, as a part of this investigation, the testing of such forms of protection for columns made from this type of aggregate as might appear to be promising. The following types of columns were accordingly tested, all from Pittsburgh gravel, all of the same effective diameter, and all reinforced with 1 per cent of spiral and 2 per cent of vertical steel:

(a) Columns with $1\frac{1}{2}$ inches of protective concrete to which 1 inch of plaster with expanded metal binder had been added.

(b) Columns cast in gypsum forms which served as protective covering, replacing nearly all the protective concrete. (1) Those without binder in the protective gypsum. (2) Those with metal binder in the protective gypsum.

(c) Columns protected by plasters of several different kinds, replacing the protective concrete. (1) Columns cast in steel forms. (2) Columns cast in a form consisting of the steel reinforcement covered with metal lath.

(d) Columns protected in the usual way with concrete, except that light expanded metal was used as a binding material to prevent the loss of protective concrete by spalling.

(1) Columns with $1\frac{1}{2}$ -inch thickness of protective concrete.

(2) Columns with $2\frac{1}{2}$ -inch thickness of protective concrete.

(e) Columns with $2\frac{1}{2}$ -inch thickness of protective concrete without binder.

III. TEST EQUIPMENT

A sectional view through furnace and loading equipment is given in Figure 1.

1. FURNACE

The furnace used for the fire tests consisted, essentially, of three fixed walls and one moveable wall which inclosed a furnace chamber 6 by 6 feet in cross section and 8 feet high. The top of the furnace was formed by a fire-brick arch. A square opening was made in this arch to permit of loading the column from above. In the course of the investigation some repair work had to be done to preserve the size of this opening, but it did not become a serious matter.

FIG. 1.—Section through test furnace

For firing the furnace natural gas was available and was used with air supplied at an average pressure of about 15 lbs./in.² Firing was done through four openings, each containing three gas burners. The burners were located near the bottom of the furnace, and baffles were provided to direct the blast upward and to spread it out over the furnace lining rather than to permit any considerable portion of it to impinge directly on the column. Flues in the bottom of the furnace communicated with an outside stack, also a vent was provided at the top of the furnace in one of the walls which permitted part of the gases of combustion to be taken out at the top for the adjustment of the temperature distribution.

2. LOADING EQUIPMENT

Load was applied to the columns in the furnace by means of a 500-ton hydraulic jack, supported by I beams extending across the top of the furnace, the load being received by four steel tension rods connecting these beams with a reinforced concrete girder extending under the furnace. The jack was operated by a hand pump to which it was connected by a flexible copper pipe. Readings were taken on a gauge attached to the pump and referred to a curve obtained by calibrating the combination of gauge, pump, and jack in a 600,000-pound testing machine. The capacity of the supporting steelwork of the equipment was rated at 600,000 pounds, and this was the limit to which columns were loaded in the furnace. Adjustment for even bearing was obtained before load was applied with a bearing block having skew movable disks.

3. TEMPERATURE MEASUREMENTS

Temperatures in the furnace and in the interior of the columns were measured by means of iron-constantan thermocouples connected to a portable potentiometer. The location of thermocouples is shown in subsequent sketches. In general, it may be said that thermocouples were located nearly midway between the ends of the column at three depths from the surface. At the depth of the vertical rods couples were located in the concrete, and others were attached to the rods themselves. Others were placed midway between the centers of the rods and the center of the column, and one couple was placed at the center of the column.

IV. MAKING OF COLUMNS

1. MIXTURE USED

Throughout the investigation the following mix was used: 1 Portland cement, 2 sand, and 4 coarse aggregate, by volume. One bag of Portland cement weighing 94 pounds net was taken to be 1 cubic foot. The sand was artificially dried to be nearly moisture free, so that the weight-volume relation did not change materially between different tests. The weight of aggregate per cubic foot having been determined, the proportions were generally obtained by weighing.

2. METHOD OF MIXING

Because of the limitations of the space available for the making of the columns and of the comparatively small quantities of concrete required at any one time all mixing was done by hand. The following routine was followed in mixing:

The sand and cement were first mixed together dry by turning with shovels three times. The entire batch, including the coarse aggregate, was then turned twice, dry, and a crater-like depression made in the pile. Water was poured into this crater and worked in to some extent, after which the batch was turned three times, water being added as needed from a sprinkling can.

3. CONSISTENCY

The consistency of the concrete made throughout the investigation was that obtained by adding from 8 to 10 per cent of water, by weight, to the dry batch. This gives, with 1:2:4 concrete, approximately maximum strength. Concrete of this consistency will stand in a low pile without running or spreading out to any great extent and will quake under local pressure. When placed in a column form with spiral reinforcements, it requires some poling to make it fill out properly against the form, and very little, if any, free water rises to the top. This consistency has two characteristics which recommend it for investigative work in which it is desired to make a rather close comparison of the effects of other variables—it is a fairly definite consistency which can be reproduced with a fair degree of accuracy in the ordinary course of hand mixing; it is not far from the ideal consistency for reinforced concrete, which building practice seems likely to approach as the importance of the use of the right amount of water in concrete becomes more generally appreciated and practice is adjusted accordingly.

4. PLACING OF CONCRETE

In placing the concrete in the forms it was thoroughly poled. There is no question that more care was taken in the making of these columns than could be expected in building practice. It must be taken into consideration in this connection that it is necessary in an investigation of this kind, in order to get reliable information from a limited number of columns, to have as little variation as possible in such factors as consistency and workmanship, otherwise results would be erratic and difficult to interpret, and in order to make them satisfactory, it would be necessary to multiply the number of tests so as to obtain averages of the results from a fairly large number of columns of each kind. In other words, it was thought that it would not be expedient to attempt to approximate average or usual building practice in the making of these columns because of the rather wide variation that may be expected in the character of the concrete and the method of placing on different building operations or even on the same operation.

5. PLACING OF THERMOCOUPLES

In order to obtain the temperature of steel rods, two holes of slightly larger diameter than the 16 gauge wire used and about 1 inch apart were drilled in each of two rods for each column. The ends of the two thermocouple wires were inserted in these holes and peened in so as to give good contact and to hold the ends in place. The couples that were not to be attached to the steel were suspended, with the juncture midway between the base plate on which the column was cast and a steel bar placed across the top of the form. The iron wire of each thermocouple extended toward the bottom of the column and the constantan wire toward the top. For each of these thermocouples one hole, accurately located, was provided in the base plate to admit an anchorage cord which could be attached to the iron wire of the thermocouple. A corresponding hole in the bar across the top of the form held a hook with a screw shank, with a nut resting on the bar. A cord was used to attach this hook to the constantan wire of the thermocouple. By screwing down the nut on the shank of the hook tension could be put on the thermocouple so that it would be stretched out in a line between the hole in the bottom plate and the hole in the top crossbar. It was not considered practical, however, to put enough tension

on the thermocouples to prevent their suffering some displacement in the course of the placing of concrete. To prevent such displacement, a frame was provided which could be left in the form to hold the wires in alignment while the greater part of concrete was being placed. The frame was left midway between top and bottom of the column until the concrete had partly covered it, after which it was pulled up as fast as the concrete was placed. Before the concrete reached the top the frame was taken apart and removed. Before the ends of the hooks were covered the strings were cut and the crossbar removed. The strings through the base plate were cut when the column was removed from the base plate.

After a considerable amount of data had been secured on the temperature progress at several points in columns of different types and from different aggregates it was considered unnecessary to continue placing thermocouples at depths beyond that of the steel. It will be noted that in tables giving temperature data columns with numbers above 71 show temperatures for the steel only.

V. METHOD OF TESTING

1. LOADING AND FIRING

In all of the tests the working load of the column was applied before the fire test was started, and this load was maintained throughout the test.³ Firing was regulated to conform as nearly as possible to the standard time-temperature curve for fire tests adopted about 1917 by 10 national technical societies and the Bureau of Standards. It was not possible in most cases to conform strictly to the standard curve during the first hour of the test, as the gas supply was not sufficient to raise the temperature of the furnace at the prescribed rate. The difference between the curve usually attainable in the test furnace and that of the standard fire test was hardly enough to be regarded as of great importance so far as the rapidity of temperature rise is concerned, but in order to compensate approximately for the somewhat slower absorption of heat by the column during the period in which temperatures were lower than those of the standard curve somewhat higher than standard temperatures were carried during an interval following the time at which the standard curve was intersected by the test curve, so that the average temperature in

³ Working loads were calculated according to the recommendations (1913) of the Joint Committee on Concrete and Reinforced Concrete.

the furnace throughout the test would approximate the average temperature of the standard test. In making this compensation furnace temperatures were not permitted to exceed to any important extent the temperature to be reached at the end of four hours according to the standard curve. Typical time-temperature curves as obtained with column 3 are given in Figure 2.

FIG. 2.—Furnace and column temperatures, 18-inch Pittsburgh gravel concrete column No. 3, with spiral and vertical reinforcement

2. DURATION OF TEST

Fire tests were of four hours' duration, except in the case of those columns which failed under their working load before the test had been in progress for four hours. It was assumed that comparatively little construction of a higher grade than that now classed as four-hour protection is likely to be done, and that the margin of safety can be judged by the excess load sustained by the column while hot at the end of the four-hour fire test. Fairly satisfactory information as to the ability of various types of columns to withstand fire tests of shorter duration than four hours can be obtained by reference to the temperature data.

At the end of the four-hour fire test, before the column had had time to cool to any considerable extent, the load was increased until the column failed, or until the maximum loading capacity of the furnace equipment (600,000 pounds) was applied without

failure. This procedure was decided on in the belief that the critical time for a column which is exposed to fire is while the fire is in progress, since at that time its strength presumably reaches its lowest point, and it must at the same time resist high stresses due to the unusual temperature conditions.

Most of the types of columns included in the investigation were made in triplicate. Two of the three were subjected to fire test and the third tested in compression without fire test. A comparison of the strength of the two fire-tested columns immediately after firing with that of the unfired column shows the extent to which the strength of the columns of this type was reduced in the four-hour fire test.

Those columns which did not fail at the end of the fire test under the maximum load of the furnace loading equipment (600,000 pounds) were tested in compression after cooling in the 10,000,000-pound machine in the engineering testing laboratory of the Bureau of Standards.

VI. AUXILIARY AND CONTROL TESTS

1. TESTS OF CEMENT AND CONCRETE

Among the possible sources of accidental variation in investigations connected with concrete is the question of variations in the character of the cement itself. In this investigation Portland cement of a single brand was used. The cement was purchased in fairly large quantities and stored in large, covered sheet-steel containers. A sample of the cement used in each column was used in a 1:2 mixture with screened Pittsburgh sand for making ten 2 by 4 inch cylinders. These were stored in a damp closet and tested at 7 and 28 days as a check on the quality of the cement. Results of these tests are given in the Appendix, Table 16. While a large variation in strength occurs, there are no abnormally low values that would indicate a cement of quality below that generally considered acceptable.

The concrete for each column was usually mixed in three batches. A sample of concrete from each batch was made into a 6 by 12 inch cylinder. These cylinders were stored in a damp closet until the column was tested and broken in compression without fire test at the same age as the column as a check on the character of the concrete, the results being given in Table 16. The average cylinder strength for concrete made with given aggregate combinations ranged from 2,260 to 3,664 lbs./in.², the

general average being higher than ordinarily obtainable under current construction conditions, which can be ascribed mainly to difference in consistency of the concrete mixture.

2. TESTS OF STEEL USED IN REINFORCEMENT

It was not considered expedient when starting the work to outline the complete program, and consequently the steel was not all purchased at one time, but both the vertical steel and the hooping used in the earlier columns were duplicated, as nearly as possible, in the materials purchased for the later ones. Results of tests of the spiral reinforcing steel are given in the Appendix, Table 15, and indicate a drawn steel of high tensile strength. No results of tests of the vertical reinforcement can be given, but the purchase specifications called for a rolled steel of the structural grade.

3. DATA FROM COMPRESSION TESTS OF COLUMNS

A large amount of data on longitudinal deformation of columns as well as both lateral and longitudinal deformation in steel and concrete were obtained in the tests of columns which were not fire tested and also of columns which did not fail at the maximum load of the furnace-loading equipment at the end of the four-hour fire test. A considerable portion of this data has no special connection with fire resistance and is not given in this publication. Typical curves which are of interest in connection with the effect of the fire test on the properties of columns which survived the four-hour fire test and the excess load imposed at the end of the fire test are subsequently given.

VII. RESULTS OF FIRE TESTS ON COLUMNS PROTECTED BY 1½ INCHES OF CONCRETE

1. ROUND COLUMNS OF 18-INCH DIAMETER, SPIRALLY AND VERTICALLY REINFORCED

Under ordinary conditions columns of the laterally reinforced type may be regarded as exceptionally safe because of the ability to undergo great deformation without actual failure. They may also be expected to give warning when heavily loaded before failure will take place. An inspection of the test data in Table I reveals great differences in the performance of hooped columns under fire conditions, some columns of this type showing comparatively little loss of strength in the four-hour fire test and others failing under their working load before the end of the test.

By contrast even square columns, of the type that is commonly regarded as most susceptible to injury by fire, survived the four-hour fire test in all cases without failing under their working load. It is evident, therefore, that fire conditions introduce a change in the relative reliability of the hooped column.

(a) COLUMNS MADE WITH PITTSBURGH GRAVEL.—The most obvious cause of the remarkable contrast between the behavior of different hooped columns under fire-test conditions is spalling. This has been observed and reported in a number of instances in connection with the effect of fire on concrete and other materials.⁴ It is commonly supposed to take place more generally in square columns than in round. However, in these investigations all aggregates which showed any tendency to spall in any type of column spalled decidedly in the fire tests of the round hooped columns. The first three columns of this type, made from the Pittsburgh gravel, showed similarity of behavior under fire. In all three cases there was evidence of failure of the protective concrete after approximately 30 minutes of firing. The appearance at the beginning of the spalling action was fairly characteristic. At some part of the surface of the column there appears what looks like a local disturbance, as if one portion of the outer material were giving way under pressure and pushing out over the adjacent material. From this point as an apex a series of cracks develop, often separate at first, but so located that as the cracks extend they unite, forming the boundaries of fairly well-developed slabs. The first disturbance is followed at fairly short intervals by others, the slabs gradually disengaging themselves from the body of the column and eventually falling off. In columns 1 and 2 the first slab fell off after approximately 40 minutes of firing; in column 3 the time was 53 minutes. In the tests of these columns there was a strong tendency for the protective concrete to separate from the rest of the column at the parting formed by the hooping. As a result the falling of a slab usually resulted in the exposure of the spiral reinforcement over a considerable area. In the tests of columns 1 and 2 the steel was first exposed after about 45 minutes of firing, the amount of protective concrete remaining on the columns being negligible after the first hour and a half. In column 3 the action was somewhat slower, but there was practically no protection after 2 hours.

⁴ Woolson, *Proc. Am. Soc. for testing materials*, 6, p. 433; Woolson, *Engineering Record*, 75, p. 98, Jan. 20, 1917; Marsland, *Red Book No. 211*, British Fire Prevention Committee; Hull, *Bureau of Standards Technologic Paper No. 130*, p. 33; Robinson, Ingberg, Wilson, Griffin, *Bureau of Standards Technologic Paper No. 184*, p. 174.

TABLE 1.—Spirally and Vertically Reinforced Concrete Columns

[Outside diameter, 18 inches. Thickness of concrete outside the steel, $1\frac{1}{2}$ inches. Reinforcement: 2 per cent vertical, 8 round rods, $\frac{3}{4}$ inch diameter; 1 per cent spiral, $\frac{1}{8}$ inch diameter, 2-inch pitch, 2 spacers. Effective area of concrete, 168.7 square inches; area of vertical steel, 3.53 square inches; effective area of column, 172 square inches; working load 141,000 pounds=822 lbs./in.²]

Aggregate	Column number	Age at time of test		Time of failure in fire test under working load		Stress at maximum load—			Maximum temperature at end of fire test—		
		Months	Days	Hours	Minutes	Without fire test	At end of four-hour fire test	Tested cold after four-hour fire test	At depth of vertical rods	Mid way between steel and center	At center of column
						Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	° C.	° C.	° C.
Pittsburgh gravel and sand	1	6	4	3	45				950	410	240
	2	6	7	4	15				1,050	460	290
	3	7	9					1,145	945	355	210
	5	6	24								
	73	4	0	3	50	6,340			980		
	74	4	0	3	20				780		
	75	4	4			4,880					
	77	4	3				1,993		660		
Pure quartz gravel and Long Island sand	78	4	0				2,120		605		
	42	4	10	3	32				990		
Long Island gravel and sand	43	4	7	3	00				990	350	150
	46	4	3	3	37				985	275	100
Elgin (Ill.) gravel and sand	47	4	5	3	40				1,000	250	105
	85	4	1					4,440	480		
	86	4	1					5,240	520		
West Winfield (Pa.) limestone and Pittsburgh sand	87	4	4			5,620					
	17	7	1					4,770	520	240	120
	18	8	17					5,320	560	180	100
Blast-furnace slag and Pittsburgh sand	20	7	4			6,890					
	48	4	0				2,700		480	85	85
	49	4	7			4,870					
New Jersey trap rock and Pittsburgh sand	50	4	21				2,260		465	110	100
	54	4	7				2,420		610	190	100
	55	4	16				3,000		560	239	110

¹ Columns 77 and 78 had expanded metal in the protective concrete.

In comparing the test results for columns 73, 74, and 75 with those for columns 1, 2, 3, and 5 (Table 1), account should be taken of the fact that columns 1 to 5 were made near the beginning of the investigation and columns 73 to 75 were made near the end of it, and therefore approximately two and one-half years later. In the latter part of the investigation columns were made for the purpose of determining the effect of a greater thickness of protective concrete on gravel concrete columns and also for determining the effect of light secondary reinforcement in the protective concrete. Although the results of the tests of columns 1 to 5 were available for comparison, it was considered best to repeat the columns of this type, so that the test results of the col-

umns with the additional thickness of protective concrete and of those with the secondary reinforcement could be compared with those of columns with the usual type of protection, made at about the same time, as well as with such columns which had been made earlier.

The concrete used in these later columns was of somewhat wetter consistency than that used in the earlier ones, due to the fact that these columns were for comparison with those in which expanded metal was placed in the protective concrete. It will also be observed that these columns were not as old when tested as the earlier ones. These two conditions probably account for the difference in strength between columns 5 and 75.

FIG. 3.—Results of tests with concrete protected round columns vertically and laterally reinforced

In the first test column 73 showed evidence of shell failure in 18 minutes, and the protective concrete was very much shattered in 45 minutes, but it did not break up into large slabs to the extent observed in the tests of columns 1, 2, and 3. The first large slab that was observed to come off fell at the end of 1 hour and 10 minutes, exposing the spiral over a considerable area.

In the fire test of column 74 evidence of shell failure was observed after 20 minutes, and the steel was exposed to an important extent at the end of 55 minutes of firing. At the end of two hours approximately 25 per cent of the protective concrete was in place.

As has been stated, the working load was kept on the columns during the fire test. In these columns, made from Pittsburgh

gravel, it was necessary to open the valve slightly to let a little oil back into the pump at frequent intervals to prevent the pressure from being increased by the expansion of the column. It was observed, however, that there was an interval, following the failure of the protective concrete, during which there was little or no evidence of expansion. After the slabs began to fall away and the surface underneath was exposed to the fire the gauge again indicated progressive expansion. The impression given by the indications of the gauge, together with the action of the outer shell of concrete, was that this shell by its own expansion assumed more than its proportionate share of the load on the column until its ultimate strength was exceeded and this portion failed. The load was thereby shifted to the column proper, which had not yet begun to expand rapidly, and the gauge would not indicate further expansion until the slabs began to fall off and the column proper received heat rapidly, when expansion was again indicated. Still later in the test the gauge would remain stationary for a long time and finally begin to indicate compressive deformation, occasional pumping being necessary to maintain the pressure. It was a common observation with columns of this kind that when it became necessary to pump occasionally to maintain the pressure the column was nearing failure.

A study of the temperature data for these columns (Table 1) shows that but little strength could have been left in the steel after the end of the third hour of firing. Temperature data are given for the depth of the centers of the vertical rods, and it is obvious that temperatures in the hooping would be higher. In the latter part of the tests the load must have been carried almost entirely by the concrete.

The Pittsburgh gravel is made up of a mixture of different kinds of pebbles, with sandstone pebbles predominating. There is a small proportion of smooth pebbles, rather small and well rounded, of what appears to be vein quartz. Examination of the concrete of these columns after fire test disclosed the fact that there had been very little disruption of individual pebbles, and that this was confined to smooth, dark colored pebbles of chert, which were found scattered through the aggregate and were invariably shattered when found in portions of the columns which were subjected to rapid heating. These pebbles made up such a small proportion of the aggregate that their influence may be considered as negligible. The spalling must be attributed to the failure of the

concrete due to overstress, rather than to the disintegration of individual pebbles.

(b) COLUMNS MADE WITH PURE QUARTZ GRAVEL.—These columns (42 and 43) were from sand and gravel from Long Island. The gravel was made up almost entirely of smooth, nearly white quartz pebbles. The beginning of spalling was first observed in column 42 after 20 minutes and in column 43 after 30 minutes. The first slab was observed to fall after 30 minutes of firing in column 42 and after 42 minutes in column 43. The uncovering process was somewhat slower in the case of column 42 than in column 43, the last large slab falling after 2 hours and 20 minutes in the case of the former, as against 1 hour and 10 minutes in the test of the latter. It is evident that concrete from this aggregate has an exceedingly strong tendency to spall. The evidence of rapid expansion in the early part of the test, which has already been described in connection with the behavior of columns which spall, was especially marked in the tests of these columns from pure quartz gravel. In the columns made from this aggregate there was practically no breaking or disintegration of individual pebbles.

(c) COLUMNS MADE WITH LONG ISLAND GRAVEL.—The behavior of columns 46 and 47 was similar to that of columns 1, 2, and 3. Spalling did not manifest itself as quickly as in 46 and 47, but its progress was rapid after the action first became apparent. Spalling, or shell failure, was observed to start after about one hour of firing, and the first slab fell about 20 minutes later in one case and after about 30 minutes in the other. In both cases there was very little protective concrete in place after two and one-half hours.

The Long Island gravel was made up of a mixture of pebbles, mainly of three kinds. There was a large proportion of large pebbles of coarse-grained granite and a considerable proportion of large pebbles of gneiss. Most of the other pebbles were of quartz. In the outer portion of the columns from this aggregate the granite pebbles were shattered and the gneiss pebbles reduced to loose-grained masses, so utterly devoid of bond that it was difficult to remove the remains of a pebble in its original form. The quartz pebbles showed only a slight tendency to disintegrate or disrupt in the fire test. It is to be noted that while this aggregate is distinctly different mineralogically from the Pittsburgh gravel, yet the effects of the fire test on the columns from the two aggregates are very similar.

(d) COLUMNS MADE WITH ELGIN (ILL.) GRAVEL.—Both the sand and the gravel used in these columns came from pits near Elgin, Ill. The chief difference between this sand and gravel and those used in the gravel concrete columns discussed up to this point was in that both sand and gravel were highly calcareous instead of highly siliceous. Differences in fire resistance are attributable, therefore, to mineralogical differences in the aggregates.

In the fire tests the two columns (85 and 86) made with this aggregate behaved very much alike. There was no spalling or cracking in either case during the four-hour fire test under working load. The gauge indicated steady expansion of the column during the fire test. When the load on the heated column was increased at the end of the fire test, the column withstood the maximum load of the equipment (600,000 pounds, or 3,480 lbs./in.²) in each case without failure. In both cases the outer concrete was much shattered by the deformation during the increased loading, and the protective concrete was found to be loose and easily removed so as to expose the spiral steel after the columns had cooled. The depth to which calcination had progressed, judging by the appearance of the aggregate, was between one-half and three-fourths inch.

(e) COLUMNS MADE WITH WEST WINFIELD (PA.) LIMESTONE.—This is a high calcium limestone with calcium carbonate content of 90 to 95 per cent.

There was no spalling on the part of either of these columns during the fire test. In the case of column 17 no cracking was observed, while in the test of column 18 a few short, vertical cracks appeared after about two hours of firing. These did not become extensive enough to be worthy of consideration in connection with the flow of heat to the interior of the column. Both of these columns were loaded to the load limit of the furnace equipment (600,000 pounds) immediately after firing was stopped. Both columns were found to be capable of holding this load, which amounted to 3,480 lbs./in.², without failure before cooling. So far as could be seen no cracking of the outer shell was produced by the application of this load to column 17. In the case of column 18, however, in which some cracks had been noted in the course of the fire test, a pair of slabs separated from the rest of the column and bulged out several inches, somewhat in the shape of a toggle (fig. 4). None of the protective concrete fell off during the test. Both columns 17 and 18 had cracks in the outer concrete after cooling.

In both cases a considerable part of the protective concrete was loose, so that it could easily be removed from the columns before they were taken out of the furnace. Several days later, before the columns were tested cold, it was found that a large part of the protective concrete which had remained on the columns when they were removed from the furnace had loosened to such an extent that most of it could easily be pried or hacked off. This weakening of the outer concrete did not appear to be due to decarbonation of the limestone, for the decarbonized portion was limited sharply to an outer layer varying in thickness from five-eighths to three-fourths inch. Furthermore, this loosening of the protective concrete was common to all the hooped columns from various aggregates after fire test.

(f) COLUMNS MADE WITH BLAST-FURNACE SLAG.—As in the case of the limestone-concrete columns, the columns from blast-furnace slag concrete stood the four-hour fire test without spalling. The only peculiar thing observed during the test of these columns was a lively snapping or popping, such as is frequently heard from burning wood. This appeared to come from little local explosions in the material next to the surface of the columns. This explanation is supported by the fact that small slabs or chips were dislodged from the surface of the columns, leaving shallow craters. The snapping began in the first few minutes of firing and subsided after about 35 minutes. The evidence of these disturbances was purely superficial and apparently of no practical consequence in the effect of the fire test on the columns. In both columns 48 and 50 a thin vertical crack was observed in the early part of the burn. It did not open wider in the course of the firing in either case and should not be regarded as having any effect on the results of the test.

(g) COLUMNS MADE WITH NEW JERSEY TRAP ROCK.—No tendency to spall in the fire test was observed in the columns from this aggregate. In the test of column 54 no cracking, spalling, or other effect was to be seen. In the case of column 55 there was an explosion after 20 minutes of firing, and a thin slab, oval in shape, about 15 inches wide and 16 or 18 inches high, was dislodged from the surface of the column about 1 foot above the middle. This slab was between 1 and 1½ inches thick at the center and tapered to a sharp edge at the periphery. The explosion and the appearance of the slab would indicate the action to be the effect of the rapid generation of steam in the concrete.

Some small cracks were observed in the latter part of the test. They were apparently unimportant, as it concerns effect on the strength of the column.

(h) **DIAGRAMS OF RESULTS AND VIEWS OF COLUMNS.**—Diagrams showing test durations and loads sustained by round columns, vertically and laterally reinforced and protected by $1\frac{1}{2}$ inches of concrete, are given in Figure 3, and typical views of columns after test are given in Figure 4.

2. COLUMNS 18 INCHES IN DIAMETER, VERTICALLY REINFORCED, WITHOUT HOOPING

The essential results of tests with columns of this type are given in Table 2 and Figure 5 and views of columns after test in Figure 6.

TABLE 2.—Round Vertically Reinforced Concrete Columns

[Outside diameter, 18 inches; thickness of concrete outside the steel, $1\frac{1}{2}$ inches. Reinforcement: 2 per cent vertical, 8 round rods, $\frac{3}{4}$ inch diameter; ties, $\frac{1}{4}$ inch diameter, 12-inch centers. Effective area of concrete, 168.7 square inches; area of steel, 3.53 square inches; effective area of column, 172 square inches; working load, 99,750 pounds=580 lb./in.²]

Aggregate	Column number	Age at time of test		Stress at maximum load—		Maximum temperature at end of fire test—		
		Months	Days	Without fire test	At end of four-hour fire test	At depth of vertical rods	Midway between steel and center	At center of column
Pittsburgh gravel and sand.....	7	7	1	Lbs./in. ²	Lbs./in. ²	° C.	° C.	° C.
	8	7	19	-----	(1) 1,365	1,010	310	210
	9	9	11	-----	1,320	630	270	130
	10	6	29	4,660	-----	700	310	180
Long Island gravel and sand.....	37	8	7	-----	1,336	-----	280	130
	38	8	22	-----	872	-----	320	160
West Winfield (Pa.) limestone and Pittsburgh sand.....	21	7	7	-----	2,150	580	240	100
	22	7	2	-----	2,180	580	230	100
	24	7	3	4,290	-----	-----	-----	-----
Pittsburgh gravel in load-bearing portion; bituminous cinders in protective concrete; Pittsburgh sand throughout.....	41	8	20	-----	1,900	530	200	110

¹ Column 7 after five-hour test was loaded to failure. Maximum stress, 1,075 lbs./in.²

(a) **COLUMNS MADE WITH PITTSBURGH GRAVEL.**—In the test of column 7 there was considerable spalling. The first evidence appeared about 30 minutes after the beginning of the test in the form of a vertical crack above the center of the column. Evidence of shell failure continued to appear steadily during the next 25 minutes and to some extent thereafter. At the end of 1 hour and 55 minutes a large slab fell, exposing a portion of one of the vertical rods. Other slabs fell, but the process was rather slow, and about

FIG. 4.—Typical views of spirally and vertically reinforced columns (3, 18, and 50) after failure when load was increased at the end of the four-hour fire test

FIG. 6.—Views of round vertically reinforced columns (8, 21, and 22) after failure when load was increased at the end of the four-hour fire test

two-thirds of the protective concrete remained in place throughout the test.

In the test of column 8 the temperature rise in the furnace was somewhat less rapid than in the other tests on account of abnormally low gas pressure; the test was, therefore, less severe in respect to the conditions which cause spalling than in the other tests. After 1 hour and 50 minutes of firing a fine crack was observed, and this was followed by others. The progress was slow, however, and the cracks did not open wide enough to have any decided effect on the rate of heat flow to the interior of the column. There was no spalling.

FIG. 5.—Round columns with vertical reinforcement and no hooping

(b) COLUMNS MADE WITH LONG ISLAND GRAVEL AND SAND.—In the test of column 37 considerable snapping was heard, beginning soon after the test was started and lasting for about 40 minutes. This was attended by the flying of small fragments, some of which flew out through the peepholes of the furnace. After the test had been in progress an hour cracking of the outer concrete was observed to start. Cracks developed rather slowly. After two hours of firing portions of the outer concrete were observed to be bulging. Portions broke up in the form of slabs as the test progressed, but none of these slabs fell off. Near the end of the test the bulging had progressed to such extent that in one place the portions of the shell appeared to be pushed out about 8 inches from their original position.

In the test of column 38 cracking of the shell began after 45 minutes of firing. At the end of one and one half hours the shell was breaking up rather rapidly, forming slabs. After the first two hours portions began to fall from a portion of the column not readily observed from the peepholes. How much of the shell fell off before the end of the test could not be ascertained, but the appearance after the furnace had cooled indicated that the amount may have been considerable.

(c) COLUMNS MADE WITH WEST WINFIELD (PA.) LIMESTONE.—There was little to note in the appearance of the columns in the tests 21 and 22. The few cracks which appeared were so fine that they were indicated mainly by the darker color of the surface of the concrete fringing them. The protective concrete remained intact during the fire test. The columns were loaded to failure while hot at the end of the fire test. After cooling it was found that with the exception of that portion which came in the region of the actual fracture of the column the protective concrete was still solid on the column.

(d) PITTSBURGH GRAVEL CONCRETE COLUMN, WITH PROTECTION OF CINDER CONCRETE.—Column 41 was made by wrapping tar paper around the outside of the reinforcement, thereby dividing the space within the form, so that one kind of concrete could be placed inside and another kind outside the reinforcement. Pittsburgh gravel concrete was used in the load-bearing portion and cinder concrete from bituminous cinders in the outer portion.

In the test of this column there were yellowish flames playing about the column during a large part of the test, indicating that gases were being distilled out of the cinders, tar paper, or both. Cracking of the protective concrete was first observed after 50 minutes of firing. The cracking was somewhat extensive, but not similar to that in the columns in which spalling took place. Cracks opened wider in the course of the test, one crack appearing to be about 3 inches wide at the widest part. None of the material fell off.

3. COLUMNS 18 INCHES IN DIAMETER, WITH NO REINFORCEMENT

These columns were made from Pittsburgh gravel and sand (Table 3). In the fire test they showed a strong tendency to spall, but the spalling action was somewhat different from that in reinforced columns from the same aggregate. In the test of column 12 evidence of shell failure was first observed after 25 minutes and in column 14 after 45 minutes. In both cases cracking,

FIG. 8.—Views of square vertically reinforced columns (25, 29, and 30) after failure when load was increased at the end of the four-hour fire test

TABLE 3.—Plain Concrete Columns

[Outside diameter, 18 inches; thickness of concrete considered as protective material, $1\frac{1}{2}$ inches; reinforcement, none; effective area, 180 square inches; working load, 81,000 pounds=450 lbs./in.²]

Aggregate	Column number	Age at time of test		Stress at maximum load—		Maximum temperature at end of fire test—		
		Months	Days	Without fire test	At end of four-hour fire test	At $2\frac{1}{4}$ inches from surface	At $5\frac{3}{8}$ inches from surface	At center of column
				Lbs./in. ²	Lbs./in. ²	° C.	° C.	° C.
Pittsburgh gravel and sand.....	12	7	10	-----	835	1,070	450	205
	14	9	23	-----	(1)	950	240	120
	15	7	10	3,650	-----	-----	-----	-----

¹ Column 14 failed under working load at end of 3 hours and 45 minutes.

breaking up into slabs, and falling of slabs progressed steadily, but rather slowly. The loss of protective concrete was more rapid than in columns with vertical reinforcement, but no hooping; it was less rapid than in hooped columns from the same aggregate. The thickness of the concrete dislodged by spalling was somewhat irregular. It appeared to be approximately $1\frac{1}{2}$ inches on the average. These columns failed suddenly with considerable shock, breaking up into large pieces which fell to the bottom of the furnace.

Fig. 7—Square columns with vertical reinforcement and no hooping

4. COLUMNS 16 INCHES SQUARE, WITH VERTICAL REINFORCEMENT

General results of tests are given in Table 4 and Figure 7 and typical views of columns after test in Figure 8.

(a) COLUMNS MADE WITH PITTSBURGH GRAVEL.—In columns 25 and 26 (Table 4) the spalling tendency was strongly exhibited.

In column 25 cracks indicating the beginning of spalling were observed after 20 minutes of firing. Cracking of the outer concrete progressed steadily. At the end of one and one-half hours the outer concrete appeared to be split loose from the column at all the corners, but none of the slabs so separated had yet fallen. At 1 hour and 50 minutes one piece from near the bottom of one of the corners fell off. So far as could be observed no more of the concrete fell from this column during the fire test and no steel was exposed.

TABLE 4.—Square Vertically Reinforced Concrete Columns

[16-inch square columns. Thickness of concrete outside the steel, $1\frac{1}{2}$ inch. Reinforcement: 2 per cent vertical, 4 rods, 1 inch diameter; ties, $\frac{1}{4}$ inch diameter, 12-inch centers. Effective area of concrete, 156 square inches; area of steel, 3.14 square inches; effective area of column, 159 square inches; working load 92,000 pounds = 578 lbs./in.²]

Aggregate	Column number	Age at time of test		Stress at maximum load—		Maximum temperature at end of fire test—	
		Months	Days	With-out fire test	At end of four-hour fire test	At depth of vertical rods	At center of column
				Lbs./in. ²	Lbs./in. ²	° C.	° C.
Pittsburgh gravel and sand	25	7	24	-----	1,005	775	160
	26	8	4	-----	830	995	165
	28	7	1	5,030	-----	-----	-----
Pure quartz gravel and Long Island sand	44	4	8	-----	680	1,000	250
	45	4	24	-----	868	1,000	280
West Winfield (Pa.) limestone and Pittsburgh sand	29	8	14	-----	2,360	660	100
	30	8	27	-----	2,420	630	100
	32	7	25	5,090	-----	-----	-----
Blast-furnace slag and Pittsburgh sand	51	4	5	-----	2,278	690	100
	52	4	26	4,700	-----	-----	-----
	53	4	12	-----	1,905	770	-----
New Jersey trap rock and Pittsburgh sand	56	4	5	-----	1,855	690	-----
	57	4	12	4,480	-----	-----	-----

In the test of column 26 cracking was observed after 14 minutes, and the breaking loose of the outer concrete at the corners progressed rapidly, the lines of separation at the surface being about 6 inches back from the corners. Slabs began to fall at the end of 33 minutes and continued until, at the end of 1 hour and 50 minutes, all the vertical rods were exposed over a considerable portion of their length. Deep vertical cracks developed near the middle of the sides of the column, and there was considerable buckling of the outer concrete in several places. The appearance of the column and the fact that it was necessary to work the pump frequently to maintain the working load indicated that the

column was on the verge of failure at the end of the fire test, failure occurring at 830 lbs./in.².

(b) COLUMNS MADE WITH PURE QUARTZ GRAVEL.—In the test of column 44 spalling started after 33 minutes and continued steadily. After 2 hours and 15 minutes of firing all the outer concrete was gone from the corners of the column with the exception of unimportant portions near the ends, exposing the column rods. In column 45 the spalling action was somewhat slower, starting in at 45 minutes and continuing until the test had been in progress approximately two and one-half hours. A large part of the protective concrete on the corners spalled off. As was the case with the other square columns already referred to, this column was in a very much shattered condition after failure.

(c) COLUMNS MADE WITH WEST WINFIELD (PA.) LIMESTONE.—In the test of column 29 some fine cracks were indicated in the third hour of the test by dark streaks on the surface of the column. Except for these there was no evidence of cracking and no spalling during the fire test. The observations in the test of column 30 were practically the same as in that of 29.

(d) COLUMNS MADE WITH BLAST-FURNACE SLAG.—In the test of column 51 a lively snapping was heard after 15 minutes of firing, accompanied by the flying of small fragments, some of which flew out of the peepholes. This subsided after a few minutes. With the exception of the pits left by the bursting of some of the individual pieces of the slag aggregate next to the surface of the column, there was no surface indication of injury to the column during the fire test. No cracks were visible and, of course, no other indication of spalling. When the load was increased at the end of the four-hour fire test, the column failed suddenly without warning and with a comparatively loud report. The observations in the test of column 53 were practically the same as in 51.

(e) COLUMNS MADE WITH NEW JERSEY TRAP ROCK.—No cracks were visible during the fire test of this column (56). At the end of the fire test the column failed under increased load without shock.

5. COLUMNS MADE WITH PITTSBURGH GRAVEL CONCRETE 12 INCHES IN DIAMETER, WITH VERTICAL AND SPIRAL REINFORCEMENT

The main results of the tests made are given in Table 5. There was considerable difference in the behavior of columns 33 and 35 in the fire test. In column 33 disturbance in the outer concrete

was indicated after 40 minutes by fine, short, vertical cracks grouped in a single curved line. Within a few minutes these

TABLE 5.—Twelve-Inch Columns

[Outside diameter, 12 inches; thickness of concrete outside the steel, $1\frac{1}{2}$ inches. Reinforcement: 2 per cent vertical, 4 round rods, $\frac{3}{8}$ inch diameter; 1 per cent spiral, $\frac{1}{4}$ inch diameter, $2\frac{3}{8}$ inch pitch, 2 spacers. Effective area of concrete, 60.8 square inches; area of vertical steel, 1.23 square inches; effective area of column, 62 square inches; working load, 51,000 pounds=822 lbs./in.²]

Aggregate	Column number	Age at time of test		Stress at maximum load—		Maximum temperature at end of fire test—		
		Months	Days	Without fire test	At end of four-hour fire test	At depth of vertical rods	Midway between steel and center	At center of column
Pittsburgh gravel and sand.....	33	7	4	Lbs./in. ²	Lbs./in. ²	° C.	° C.	° C.
	35	10	5	-----	1,145	690	560	480
	36	7	6	4,840	(1)	-----	-----	-----

¹ Column 35 failed under working load at end of two hours.

cracks had widened and others had appeared. The outer concrete gradually broke up into slabs, which, however, were still in place, although some cracks opened wide, so that the spiral steel could be seen through one of them in the latter part of the test. After one and one-half hours of firing the shell of outer concrete was observed to be bulging considerable in various places. After the test had been in progress for about three and one-half hours a small slab of concrete fell off, exposing the spiral steel in an area of something like a square foot. This column, in spite of the spalling tendency which was strongly exhibited, had practically the full protection of its protective concrete, except during one-half hour of the test, and of a very large part of it during the entire test. In the test of column 35 spalling was evidenced after 40 minutes and progressed rapidly, a large slab of the protective concrete falling at the end of 50 minutes. A large part of the protective concrete had fallen in 1 hour and 10 minutes from the start of the test. At the end of two hours the column failed without shock under its working load.

VIII. COLUMNS WITH ADDITIONAL INSULATING MATERIAL IN THE FORM OF PLASTER

In the case of columns in existing buildings, one of the simplest ways of securing additional protection would be by applying plaster to the column. This raises the question as to whether

such protective material will stay in place during a fire, particularly if applied to gravel concrete, which itself has a tendency to spall and come off. The test data of Table 6 compared with the data of Table 1 show the results obtained from the addition of a

TABLE 6.—Columns Protected by Concrete and Plaster

[Outside diameter of concrete, 18 inches; column diameter increased to 20 inches by plastering; thickness of protective material, 2½ inches. Reinforcement: 2 per cent vertical, 8 round rods, ¾ inch diameter; 1 per cent spiral, ⅜ inch diameter, 2-inch pitch, 2 spacers. Effective area of concrete, 168.7 square inches; area of vertical steel, 3.53 square inches; effective area of column, 172 square inches; working load, 822 lbs./in.²]

Aggregate	Column number	Age at time of test		Stress at maximum load—		Maximum temperature at end of fire test—		
		Months	Days	At end of four-hour fire test	Tested cold after four-hour fire test	At depth of vertical rods	Midway between steel and center	At center of column
Pittsburgh gravel and sand.....	14	12	2	Lbs./in. ²	Lbs./in. ²	° C.	° C.	° C.
	16	5	16	-----	5,970	375	155	90
	76	6	25	3,270	5,615	410	160	110
West Winfield (Pa.) limestone and Pittsburgh sand.....	19	10	23	-----	6,050	410	135	90

¹ Columns 4, 6, and 19 were given the additional protection of 1 inch of plaster composed of Portland cement and sand with a small percentage of lime hydrate. The plaster covering was reinforced with light expanded metal.

² Column 76 was plastered with a mixture of Portland cement and crushed bituminous cinders, increasing the thickness of protective material from 1¼ to 2¼ inches. No metallic binder provided for the plaster.

thickness of approximately 1 inch of plaster to columns which were originally built with 1½ inches of protective concrete. It was anticipated that the plaster would not stay in place during the fire unless reinforcement or binder was used to hold it in place, and in columns 4, 6, and 19 this was provided. The plaster used on these three columns was of the following composition:

First coat: 1 part, by volume, Portland cement; 2 parts, by volume, sand; hydrated lime to the amount of 10 per cent, by weight, of the cement. Second coat: Same as above, except that hydrated lime to the amount of 15 per cent, by weight, of the cement was added. No finish coat was applied. The expanded metal used was of 16-gauge steel (0.0625 inch), 2-inch mesh, and weighed 1.67 lbs./yd.².

The expanded metal was furred out approximately one-half inch from the surface of the column, so that it occupied a position at about the middle of the thickness of the plaster. Later experience in the use of light metal reinforcement in protective plaster

has indicated that it would be practical and probably less expensive to apply the first coat of plaster and after this coat had hardened sufficiently apply the expanded metal or other reinforcing material directly over the first coat and then complete the plastering. In case the main object was to safeguard against the falling off of the protective concrete, the secondary reinforcement could be applied directly over the original concrete and one coat of plaster applied to protect the secondary reinforcement as well as to provide additional insulation.

Columns 4 and 6 were the same before plastering as columns 1, 2, and 3 (Table 1), all of which spalled in the fire test, losing the protective concrete and giving poor results.

Column 4 was tested 66 days after plastering. Cracks began to be visible in the surface of the plaster after 1 hour and 20 minutes of firing and continued to appear during the next hour. After that the cracks, which were fairly regular and generally vertical in direction, seemed to widen gradually during the remainder of the test.

Immediately after the completion of the four-hour fire test the load was increased to 600,000 pounds (3,480 lbs./in.² of effective area) without producing failure or any observable change in the appearance of the column. After cooling the plaster covering was found to be cracked into seven long strips, like staves, separated by fairly regular, generally vertical cracks, the greatest width of crack being approximately one-half inch. None of the plaster had fallen off and none of it was bulging greatly.

When the plaster was removed, it was found that the protective concrete was very much broken up, giving an appearance similar to unplastered columns at the period of test when the shell was breaking up but the slabs had not yet started to fall off. Whether this breaking up of the protective concrete of column 4 took place during the fire test or when the load was increased at the end of the fire test could not be determined. It may be said in this connection that when column 18, which was a limestone concrete column with spiral reinforcement, was loaded at the end of the fire test a portion of the protective concrete buckled, due to the deformation, although there had been no spalling during the fire test. It seems probable, judging from this and other observations made in the course of the investigation, that the protective concrete of column 4 may have cracked during the fire test, and that the deformation which occurred when the load was increased

broke the already cracked shell into slabs. At any rate, the material all stayed in place during the fire test, and, so far as insulation was concerned, was approximately as effective as if it had not been broken. The final temperatures in this column (Table 6) and the strength of the column when tested cold after the fire test testify to the effectiveness of the combination of concrete and reinforced plaster which protected it.

The record of the test of column 6 is almost the same as that of 4. A small slab of the outer coat of plaster was observed to have fallen away after 25 minutes of firing. With this exception, there was no essential difference between the behavior of this column and that of column 4.

Column 19, which was a limestone concrete column covered with 1 inch of reinforced plaster, the same as 4 and 6, was tested 50 days after it was plastered. The cracking of the plaster observable during the test appeared to be less extensive than in the tests of columns 4 and 6. The first cracks seen were observed at the end of 1 hour and 15 minutes. At the end of the fire test only two small cracks, each about 1 foot long, were visible. The increase of load to 3,480 lbs./in.² at the end of the fire test produced no noticeable change in the appearance of the column.

When this column was examined after cooling, it was found that there were seven fairly well-defined vertical cracks, some continuous and the others nearly so, extending from the top to the bottom of the exposed portion of the column. The plaster sounded hollow over the entire exposed portion and was soft and friable throughout its thickness, though softer in the outer than in the inner portion. The concrete under the plaster was soft near the surface, being fairly hard at a depth of three-eighths to one-half inch.

The plaster on the half of the column facing the door of the furnace was soaked with water at intervals during the day after the test to try the effect of recovery. After standing five days there was no apparent difference between the condition of this portion of the plaster and of that which had not been watered after the test.

On the removal of the plaster it was found that the limestone in the concrete next to the surface of the original column had been decarbonated. The depth of decarbonation was small, but the distribution was fairly uniform over a large portion of the surface of the column. The protective concrete was not broken up, as

in the case of the gravel concrete columns 4 and 6, but after standing a few days following the test was obviously unsound and continued to loosen and show signs of disintegration. Nearly all of it was removed before the final load test of the cold column was made.

Had deformation measurements been made, or if the columns could have been loaded to failure while hot, in these fire tests, it is probable that considerable difference would have been observed between the behavior of this column, with its $2\frac{1}{2}$ inches of protective material, and that of 17 and 18, similar columns without the additional protection of the plaster. The ultimate strength of columns 17 and 18 when tested cold after the fire test was so high that it can hardly be said from these results alone that the additional protection was needed in columns of this type, although the ultimate strength of 19, which had the additional protection, was distinctly higher. It may be judged by a comparison of the final temperatures (Tables 1 and 6) that column 19 had a considerably greater margin of safety and presumably suffered considerably less deformation in the fire test than 17 and 18.

The results of the tests of these three columns support the assumption, based on the expansion characteristics of quartz and granite, that there is not much difference between the effect of heat on concretes in which these minerals predominate and the effect on concretes with a more favorable mineralogic composition, so long as such insulation is provided that the temperatures in the load-bearing portion of the member do not reach the region at which steel begins to suffer rapid reduction in strength. The ultimate strength of these columns had been reduced so slightly as to justify the conclusion that structures protected so that temperatures in the steel and load-bearing concrete would not exceed 400° C. (752° F.) in a fire are safe against serious structural damage by fire.

Column 76 was one that had been made for the purpose of trying the effect of ordinary metal lath, such as is used as a base for plaster, imbedded in protective concrete to prevent spalling. It was found that the concrete did not fill out properly against the form when this material was within the form, and that the result of the experiment was a column which required plastering to give it a good appearance. It was decided to use this column for a test of the performance of a kind of plaster made from Portland cement and crushed bituminous cinders, the latter taking

the place of sand. Where the metal lath was exposed and the column needed added material simply to round it out, this was done with plaster made from cement and sand.

The column was then plastered with a 1:3 mixture of Portland cement and crushed bituminous cinders. It had been found in a separate investigation of the fire resistance of different kinds of plasters, the results of which have not yet been published, that plaster made from Portland cement and cinders, the latter being crushed to a suitable fineness to take the place of sand, had expansion characteristics entirely different from and apparently much more favorable than those plasters made from cement and sand. Columns 76 and 69a were accordingly plastered with such a mixture. The cinders were the refuse from bituminous coal burned under boilers. The composition of these cinders, as shown by a proximate analysis, was as follows:

	Per cent
Volatile combustible.....	10.54
Fixed carbon.....	28.33
Ash.....	61.13
Total.....	100.00

Two coats of plaster were applied with a trowel. No metal lath or other secondary reinforcement was used to hold this plaster in place.

In the fire test a patch of the outer coat approximately 18 inches wide and 4 feet high fell off after 10 minutes of firing. At the end of 20 minutes a long and rather wide crack was showing in the plaster on one side of the column, and the entire surface of the plaster was aglow. Large portions of the outer coat of plaster fell off and cracks opened in the inner coat. After 2 hours and 40 minutes the inner coat was bulging out and large cracks had opened up in it. A large portion of it appeared to be ready to fall off. Small portions fell off before the end of the test.

The most important information gained from this test is that bearing on the properties of the plaster made from cement and crushed bituminous cinders. Although this material gave satisfactory results on another column (69a, Table 7), its performance in the test of 76 was not such as to justify recommending it for use as protective material without some light metal mesh to hold it in place. It seems probable that a plaster made from Portland cement, crushed cinders, and a small proportion of asbestos might give good results, especially if a somewhat better grade of cinders were used.

IX. COLUMNS PROTECTED BY PLASTER IN THE PLACE OF PROTECTIVE CONCRETE

The objection to the addition of plaster over columns with reinforcement to hold it in place is that it adds to both the size and the cost of the columns. If the protective concrete could be left off and plaster used in its place, the increase in size would be avoided and to some extent the increase in cost. It was thought worth while to make tests to determine what could be accomplished in this way. The tests made and the results obtained are given in Table 7. A number of columns (63, 65, 71, and 88) were made with the same reinforcement and the same effective area as the 18-inch columns, but 16 inches in diameter. This left 1 inch of protective material to be added all around to increase the thickness of protective material to $1\frac{1}{2}$ inches and the diameter of the column to 18 inches.

TABLE 7.—Columns Protected by Plaster Replacing Concrete Protection

[Outside diameter, 18 inches. Protective material applied by plastering. Reinforcement: 2 per cent vertical, 8 round rods, $\frac{3}{4}$ inch diameter; 1 per cent spiral, $\frac{1}{16}$ inch diameter, 2-inch pitch, 2 spacers. Effective area of concrete, 168.7 square inches; area of vertical steel, 3.53 square inches; effective area of column, 172 square inches; working load, 822 lbs./in.²]

Aggregate	Column number	Age at time of test		Stress at maximum load—		Maximum temperature at end of fire test—		
		Months	Days	At end of four-hour fire test	Tested cold after four-hour fire test	At depth of vertical rods	Mid-way between steel and center	At center of column
				Lbs./in. ²	Lbs./in. ²	° C.	° C.	° C.
Pittsburgh gravel and sand	1 63	9	17	1,770	-----	590	185	90
	2 65	4	26	-----	4,935	440	220	100
	3 66	4	4	1,290	-----	765	335	150
	4 67	4	22	-----	5,345	185	95	95
	5 71	4	0	2,455	-----	570	250	110
	6 72	4	0	1,280	-----	780	-----	-----
	7 88	4	1	3,120	-----	510	-----	-----
	8 89	4	1	1,885	-----	685	-----	-----
	9 90	5	14	2,000	-----	675	-----	-----
	9 69a	-----	-----	3,200	-----	520	245	175

¹ Column 63 was made 16 inches in diameter and plastered with a mixture of Portland cement, lime hydrate, and sand, increasing its diameter to 18 inches.

² Column 65 was made 16 inches in diameter and plastered with a special plaster containing Portland cement, asbestos, and sand, increasing its diameter to 18 inches. This column did not fail at the end of the four-hour fire test under the maximum furnace load, 3,480 lbs./in.².

³ Column 66 was cast in a form made by covering the spiral reinforcement with metal lath and plastering on the metal lath with cement plaster.

⁴ Column 67 was made by pouring concrete in a form made of metal lath wrapped around the reinforcing steel, column then plastered with a mixture of gypsum, lime, and kieselguhr. Poultry netting used for binder in plaster. Total thickness of protective material, $1\frac{1}{2}$ inches; thickness of plaster, approximately 1 inch. This column did not fail at the end of the four-hour fire test under the maximum load of the furnace loading equipment, 3,480 lbs./in.².

⁵ Column 71 was made 16 inches in diameter and plastered with a mixture of cement, lime hydrate, and sand, increasing its diameter to 18 inches.

⁶ Column 72 was cast in a form made by covering the spiral reinforcement with metal lath. Protective material added by plastering with a mixture of Portland cement, lime hydrate, and sand.

⁷ Column 88 was a duplicate of 65.

⁸ Columns 89 and 90 were cast in a form made by covering the spiral reinforcement with metal lath. Protective material added by plastering with a mixture of lime hydrate, gypsum, and sand. Total thickness of protective material, $1\frac{1}{2}$ inches. Thickness of plaster approximately 1 inch. No metallic binder in plaster.

⁹ Column 69a was originally cast in a gypsum form (see Table 8). Column was subjected to four-hour fire test in the gypsum form. At the end of four-hour fire test it did not fail under the maximum furnace load, 3,480 lbs./in.². After fire test gypsum form removed and protective material added by plastering on concrete with a mixture of Portland cement and crushed bituminous cinders.

1. CEMENT AND SAND PLASTER ON CONCRETE

Columns 63 and 71 were plastered with a mixture of 1 part Portland cement, 1/10 part hydrated lime, and 2½ parts sand, by volume. The plaster was applied with a trowel. Before plastering the surface of the column was hacked with a mason's point and hammer, the cuts being about 1½ inches apart all over the column. After wetting, the surface was covered with a bond coat about one-fourth inch thick consisting of one part Portland cement and approximately one-half part of sand. This was scratched and covered the following day by the scratch coat and the brown coat.

Column 63 was tested 53 days after plastering. As soon as the interior of the furnace had acquired a fair degree of visibility within the first 10 minutes of firing a long crack was observed which appeared to extend from near the top to the bottom of the column. The position of this crack was such that it could not be seen well enough to judge as to its width or depth. Other cracks opened one after another and at the end of 35 minutes a portion of the plaster was bulging. Cracks became wide gaps through which the second coat of plaster was visible, and at the end of 52 minutes the outer coat of plaster began to fall off. About half of the scratch coat (not the bond coat) was exposed very soon after the plaster began to fall. At that time there were no cracks visible in the scratch coat.

At the end of 1 hour and 20 minutes the remaining portions of the outer coat were considerably broken up and portions continued to fall at intervals, but this action was slow. Cracks appeared and widened progressively in the scratch coat, but so far as could be observed all of the scratch coat stayed on during the fire test, though some of it came off when the column failed in the load test following the fire test, and more of it came off during the cooling. In this case the second coat applied over the bond coat is referred to as the scratch coat.

Column 71 was plastered when the column was 14 days old and was tested 107 days after it was plastered. The behavior in the fire test was so nearly like that of column 63 that no separate account of the test is necessary.

2. CEMENT, ASBESTOS NAILING COMPOUND, AND SAND PLASTER ON CONCRETE

Columns 65 and 88, like 63 and 71, were made 16 inches in diameter to be increased to 18-inch diameter, with 1 inch pro-

protective material applied by plastering. The plaster used on these columns was a mixture composed of 1 bag (94 pounds) Portland cement; 1 bag (100 pounds) of the asbestos compound, and 2 cubic feet of sand. The nailing compound was a proprietary material, which examination showed to be composed almost wholly of short fibered and granular asbestos.

Both columns were hacked before plastering. The plaster was applied directly on the hacked surface after wetting, in the case of 88. Before the scratch coat was applied to 65 a belt 2 feet wide, extending downward from a level 3 feet below the top of

FIG. 9.—Furnace and column temperatures, 16-inch Pittsburgh gravel concrete column No. 65, protected by 1 inch of Portland cement-asbestos-sand plaster

the column, was plastered with a bond coat consisting of 3 parts Portland cement to 1 part sand. The scratch coat was applied immediately after this bond coat without waiting for it to set and without scratching it. With the exception of the 2-foot belt having the bond coat, the scratch coat was applied directly to the hacked surface of the concrete.

In the fire tests of both of these columns cracks appeared in the surface of the plaster, but they were not of such extent as to be considered important. All the plaster stayed in place throughout the four-hour fire test in both cases and afforded moderately good protection compared with an equal thickness of concrete. The temperature curves for column 65 are given in Figure 9. It will

be noted that the temperatures attained in the steel of limestone concrete and of slag concrete columns were about the same as those attained in these plastered columns.

3. COLUMNS CAST IN METAL LATH FORMS

Consideration was also given to the saving that might be effected, in the case of columns that were to be protected by plaster in place of the usual protective concrete, by using metal lath, covering the spiral reinforcement, as a form. As shown in Table 7, four columns were made in this way. One column (66) was made in a form consisting of metal lath covered with plaster. The metal lath was wrapped around the spiral reinforcement and plastered, the concrete being poured in the resulting form after the plaster had set. Observations made during the making of this column indicate that this would not be as satisfactory a method as that of pouring the concrete in the metal lath basket first and plastering the column afterward.

In placing the metal lath to serve as a form over the steel reinforcement care was taken to place the lath right side out, or right side up, so that the concrete could not escape as readily as if the lath were placed the other way. In making column 67 the consistency was kept sufficiently fluid so that the concrete would spread out somewhat on the mixing floor instead of standing up in a mound. It was not as wet, however, as could be made in hand mixing and not as wet as is commonly used in construction work. The concrete placed in the lower half of the column was well poled during the placing and filled out against the spiral and around the spiral steel fairly well. A little mortar oozed out through the metal lath and trickled down, but the loss of material was not important. The concrete was not so well poled during the pouring of the upper half, and in consequence did not fill out so well around the spiral steel and against the lath. In some places large voids remained after the concrete was placed. In spite of these voids the column showed good strength when tested cold after the four hour fire test.

The consistency used in making column 72 was considerably wetter than in the case of 67; it was wet enough to spread out rather thinly over the floor, but not wet enough for the water to separate to any great extent. It was about as thin as it is practical to make by hand mixing. All the concrete was mixed in one batch and the form filled quickly up to within 3 feet of the top. Pouring was then stopped for a short time and the metal

lath hammered moderately outside the poured portion in an effort to make the concrete fill out properly. The remaining portion was poled moderately during the pouring. Over a large portion of the column the concrete did not fill out completely against the metal lath and around the spiral steel. The coarse aggregate banked up against the spiral and held the fine material back. Not enough concrete passed through the spaces in the spiral to fill the small amount of space between the spiral and the lath. Approximately a gallon of thin mortar collected at the bottom of the column, on the floor, during the operation. The concrete was placed quickly in this column so as to determine whether any considerable pressure would develop against the metal lath form in the lower portion, due to the weight of the concrete above. The pouring was completed within approximately 30 minutes. Practically all the pressure was exerted against the spiral instead of against the metal lath. In the case of a concrete in which the maximum size of coarse aggregate was much smaller than that in this gravel, the results would unquestionably be somewhat different, but it is doubtful if the pressure exerted on the metal lath would be excessive in ordinary construction work.

In making columns 89 and 90 it was found that there was very little difference between the results obtained in trying to make the concrete fill out well against the metal lath with concrete that was about as wet as could be produced with hand mixing and that which was somewhat stiffer. In either case there was a tendency for the mass of the concrete to bank up against the spiral, leaving holes or pockets which did not fill up because the soupy material which would separate out from the concrete was too thin to be retained by the metal lath and would trickle into these pockets and out again. How much difference this imperfect filling would make in the strength of a column is somewhat problematical. An examination of these columns before they were plastered gave the impression that the strength would probably be practically the same if the concrete had filled out perfectly. The concrete did not make contact with the inside of the spiral at all points, and a considerable portion of the outside of the spiral was not covered with cement. The strength shown by column 67 when tested cold after the four-hour fire test shows that this was a good column, imperfectly filled out as it was. This was the only column made in the metal lath forms which

gives much information as to the strength of such columns because the others were not well enough protected to be expected to show high strength at the end of the fire test.

It is probable that if this general method of making columns should prove to be useful a better covering than the ordinary metal lath would be devised for the purpose.

(a) COLUMNS PROTECTED BY CEMENT-LIME-SAND PLASTER ON METAL LATH FORMS.—The protective material on columns 66 and 72 was the same, viz, plaster made from 1 part Portland cement 1/10 part hydrated lime, and $2\frac{1}{2}$ parts sand, by volume. In the case of column 66 the metal lath was placed on the steel and plastered before the concrete was placed. The concrete was placed in the metal lath form of column 72 before plastering. In both cases the plaster was applied with a trowel and contained no metal mesh to hold it in place, with the exception of the metal lath on which it was applied. The plaster on 66 had four months and that on 72 had about three and one-half months in which to set and dry out before being fire tested. The behavior of the two columns under fire was so similar that it is sufficient to give an account of the test of 72.

A large patch of the outer coat of plaster fell from the lower part of this column within the first 12 minutes of firing. This seemed to be the outer half of the outer coat, as no scratches were visible in the surface exposed. At the end of 16 minutes a patch of the scratch coat was exposed and a portion of the outer plaster was observed to be bulging. Plaster continued to drop off, and at the end of 25 minutes about one-third of the scratch coat appeared to be exposed. After that the action was slower, about half the scratch coat appearing to be exposed at the end of the first hour. After the first hour there was not much change in the appearance of the column except that cracks appeared in the exposed portions of the scratch coat.

After the column had cooled it was found that very little of the plaster had fallen from the upper third of the column. Of the remainder about half had lost the outer portion of the outer coat and the other half had lost all the outer coat, exposing the scratch coat. According to this estimate, about one-third of the scratch coat was exposed, although it was all in place. There appears to be some bond between all the layers of plaster, and the scratch coat was well anchored to the metal lath. The protection afforded by this kind of plaster, with no additional reinforcement to hold

the outer portion in place, can not be regarded as satisfactory, although the results were somewhat better than those shown by the ordinary gravel concrete protection. It would obviously be desirable in case columns or other members were to be plastered for fire protection to use a plaster that would stay in place under fire and also one having better insulating properties.

(b) COLUMN PROTECTED BY SPECIAL INSULATING PLASTER ON METAL LATH FORMS.—Column 67, like 72, was cast in a metal lath form and plastered afterwards. Some preliminary work had been done to determine the properties of various combinations of cement, kieselguhr, lime, and gypsum with the purpose of finding, if possible, a combination which would make a plaster of good insulating efficiency and of such physical properties that it would stay in place under fire conditions without any special binder or reinforcement to hold it in place. One of the most promising mixtures was selected for the protection of column 67, but on account of a tendency to shrink when heated it was thought best to make some extra provision against portions falling off to be certain of obtaining a determination of the insulation afforded by the entire thickness of plaster. The mixture used consisted of 56 per cent neat gypsum plaster, 24 per cent hydrated lime, and 20 per cent kieselguhr (infusorial earth), by weight. The plaster was applied in three coats, followed by a thin finish coat of gypsum plaster and hydrated lime. After the second coat was applied the column was covered with a light 2-inch mesh poultry netting, drawn fairly tight and wired where the edges overlapped. The third coat of plaster concealed the poultry netting, the finish coat simply serving the usual purpose of giving a good external appearance.

In the fire test most of the finish coat came off within the first 15 minutes. After the first 20 minutes cracks appeared in the surface of the third coat of plaster. These were irregular and extended in various directions, but most of them were approximately horizontal. These widened slowly as the test progressed. At the end of the first two hours the widest cracks appeared to be a little over one-eighth inch wide at the surface. The main cracks formed irregular checkers, approximately 9 inches across. Finer cracks were visible within the boundaries of these areas.

At the end of the four-hour fire test the widest cracks appeared to be about three-sixteenths inch wide at the surface, and all the plaster, with the exception of the finish coat, appeared to be in

place. The load was immediately increased to 3,480 lbs./in.². The column withstood this stress without any visible effect.

When the column was examined after cooling, there was found to be practically no bond left between the second coat of plaster and the third coat. Over a considerable portion of the column there was still a fairly strong bond between the inner coat and the second coat. The outer coat was soft and easily reduced to a powder. The middle coat was considerably harder and firmer. The first coat was sufficiently hard and well enough bonded to

FIG. 10.—Furnace and column temperatures, 16-inch Pittsburgh gravel concrete column No. 67 cast in metal lath form and protected by 1 inch of gypsum-lime-Keiselguhr plaster

the column so as not to be removed with tools without some difficulty.

Just how this column would have fared without the poultry netting to hold the outer plaster in place is, of course, problematical. It may be that if a reasonable proportion of asbestos were included in the mixture for the outer coat it would stay in place without any metal mesh like the poultry netting, but this was not tried. The outstanding feature of this test was the superior protection afforded by this plaster as shown by the low final temperatures attained (Table 6 and fig. 10). It should be noted that the total thickness of protective material on this

column was only $1\frac{1}{2}$ inches, and that the protection was much more effective than that of columns 4, 6, and 19, which totaled $2\frac{1}{2}$ inches in thickness. Even columns 68 and 69, with a total thickness of $2\frac{1}{2}$ inches protective material, $2\frac{5}{8}$ inches of which was gypsum, were not as well protected, as shown by the final temperatures (Table 8), as was this column. One inch of this special plaster gave better protection, judged by the temperatures in the column at the end of the four-hour fire test, than $2\frac{5}{8}$ inches of gypsum (plaster of Paris), which is known to have exceptional heat retarding properties.

It is not the intention to recommend the use of this particular mixture as a protective material—further investigation is likely to produce better ones. It does seem worth while, however, to call attention to the fact that a comparatively thin coating of a material with the insulating properties of this plaster would give better protection than the usual $1\frac{1}{2}$ or 2 inches of protective concrete and that the saving in size and weight would be considerable.

4. GYPSUM-LIME-SAND PLASTER ON COLUMNS CAST IN METAL-LATH FORM

In a separate investigation that has already been referred to a number of combinations of gypsum, lime, and sand were studied to determine whether any combination of these three materials would give a plaster which would neither shrink nor expand a great deal under fire-test conditions and which would give good protection to a column without any special reinforcement or binding material to hold it in place. As might be expected, it was found that in those mixtures in which the expansion of the sand is most nearly balanced by the shrinkage of the other materials expansion is shown in the first few minutes of firing, followed by shrinkage after that time. Of the mixtures that were made in the course of the work the most promising seemed to be one in which the proportion of neat gypsum plaster, hydrated lime, and sand was 50:20:30, by weight. Two columns, 89 and 90, which had been cast in metal-lath forms were plastered with this mixture. No poultry netting or other reinforcement was used to hold the plaster in place. In the fire test the outer portions of the plaster began to split open and fall off in large slabs in the first few minutes of firing, and after approximately one hour practically no plaster remained except the first coat applied. This stayed on throughout the four-hour test. It will be seen by a comparison

FIG. II.—Views of columns (4, 66, and 76) protected by plaster after failure under increased load after withstanding the four-hour fire test

of data (Table 7) that the insulation was somewhat more effective than that on 66 and 72, which were made in the same way but covered with cement-sand plaster.

5. CEMENT-CINDER PLASTER ON CONCRETE

Column 69a was originally 69, which, as shown in Table 8, was cast in a gypsum form. It was judged, both by the apparently good condition of the outer concrete after the column had been stripped of the form and by the comparatively low temperatures attained in the fire test, that this column, after having been subjected to a four-hour fire test and to a load test of 3,480 lbs./in.² at the finish of the fire test, was still suitable for use in a second fire test to test the behavior of cement-cinder plaster. It was accordingly plastered by the trowel method with a mixture of Portland cement and crushed bituminous cinders, 1:3 by volume. The cinders were of the same grade as those used for the plaster on column 76 (p. 667). The thickness of plaster required to bring the diameter of the protected column to 18 inches and the total thickness of protective material to 1½ inches was approximately 1 inch.

In the fire test horizontal cracks, apparently caused by shrinkage, appeared gradually in the first hour of the test and a flickering, slightly luminous flame, seemingly supported by gas issuing from the cracks, played about the column. After the first hour but little change in the appearance of the column was observed. The horizontal cracks widened somewhat, and at the end of the third hour a long, irregular, vertical crack was observed. All the plaster remained in place throughout the fire test. On examination after cooling the plaster was found to be loose, except near the ends of the column.

The behavior of the plaster on this column was consistent with the results of tests made of such plaster in the separate investigation already referred to. However, in the case of column 76 (Table 6) a plaster of this kind failed to stay in place in the fire test. It should be noted, however, that a poor grade of cinders was used. The fact that in separate tests slabs made from this sort of material showed extremely little expansion, compared with specimens made from cement-sand plasters, indicates that the possibilities of fire-resistive plasters made from crushed cinders instead of sand are worthy of further investigation. Anthracite cinders are probably superior for the given purpose to those used

in these tests. It is also worth while to consider in this connection the results of the tests of columns 65 and 88, which were protected by the cement-asbestos-sand plaster. It seems probable that some combinations of cement and cinders with asbestos or similar material would have excellent fire-resistive properties, and that, on account of the cinders having much more favorable expansion properties than the sand, a comparatively small proportion of the asbestos compound or other similar material would suffice to give the plaster the properties necessary for good results.

A comparison of results obtained with plasters and also with columns cast in gypsum forms is given in Figure 12.

FIG. 12.—Results of tests of typical plastered columns and columns cast in gypsum forms

X. COLUMNS CAST IN GYPSUM FORMS

On account of the well-known heat retarding properties of gypsum in the form of plaster of Paris it seemed desirable to try out the possibilities of this material for the protection of gravel concrete columns. If such a material were to be applied in the form of plaster, the cost of application would be considerable. If it were made up into forms, eliminating the cost of steel or wood forms, the additional cost for material and application would be partially compensated for. Forms were accordingly made in hollow cylindrical sections so fashioned at the ends as to be self-centering when set up, one on another. Forms were made in two sizes, the first 17 inches internal and 23 inches external diameter and 21 inches long; the other $15\frac{7}{8}$ inches internal and $20\frac{3}{16}$ inches external diameter by 21 inches long.

TABLE 8.—Columns Cast in Gypsum Forms

[Outside diameter of concrete, 15½ inches; thickness of form, 2⅝ inches; total thickness of protective material, 2⅜ inches. Reinforcement: 2 per cent vertical, 8 round rods, ¾ inch diameter; 1 per cent spiral, ⅜ inch diameter, 2-inch pitch, 2 spacers. Effective area of concrete, 168.7 square inches; area of vertical steel, 3.53 square inches; effective area of column, 172 square inches; working load, 822 lbs./in.²]

Aggregate	Column number	Age at time of test		Stress at maximum load—			Maximum temperature at end of fire test—		
		Months	Days	With-out fire test	At end of four-hour fire test	Tested cold after four-hour fire test	At depth of vertical rods	Mid-way between steel and center	At center of column
Pittsburgh gravel and sand.....	160	2	0	Lbs./in.²	Lbs./in.²	Lbs./in.²	° C.	° C.	° C.
	61	4	7	-----	1,205	-----	810	260	90
	68	4	0	-----	2,800	-----	185	150	110
	69	4	2	-----	-----	5,420	305	95	85
	70	4	3	-----	6,480	-----	190	90	90

¹ No anchorage was provided for the gypsum form on column 60. Form was anchored to concrete of column 61 by means of wires. In the forms for columns 68, 69, and 70 light metal reinforcing material, poultry netting, or expanded metal was used.

² Column 69 did not fail under the maximum load of the furnace equipment, 3,480 lbs./in.² and was subsequently tested as column 69a with plaster protection.

These sections as made in the laboratory were cast in plaster of Paris molds, such as are used in making pottery molds. They were made from a second settle gypsum plaster. It was the intention to make the forms as dense as possible, and it was found that about the lowest ratio of water to gypsum that could be used successfully under working conditions as they existed was 41:59. This mixture made good hard forms.

The cylindrical sections were built up one on another to the required height for the column, the steel was placed inside, centered, and the concrete placed in the usual way. The gypsum form was saturated, or nearly saturated, with water before the concrete was placed.

Only two columns (58 and 59) were made in forms with 23-inch external diameter. These columns, having a diameter of spiral of approximately 15 inches, had a total thickness of protective covering of 4 inches, of which 2½ inches were gypsum. The results of the tests of these two columns are not given in tabular form. There was sufficient similarity between the observations made in the two fire tests so that an account of one (58) will serve all essential purposes.

As soon as the furnace became sufficiently clear to make the column visible a fine crack about 4 feet long and nearly vertical was observed. Within a few minutes two other cracks, one on each side of the first, were observed. At the end of the first 20

minutes other long cracks were visible, and the characteristic checking, like that in the surface of mud which has dried in the sun, was beginning to show. All the cracks widened gradually as the test progressed. At the end of two hours a piece of the middle section of the form had fallen out. The width of this piece was about 15 inches. Within the next 15 minutes pieces of gypsum covering fell off in quick succession, leaving practically none of it in place excepting the top and bottom sections, which were only partially exposed.

During the remainder of the test the exposed concrete cracked and spalled to some extent, but not a great deal of the material actually fell off.

When the load was increased at the end of the four-hour fire test, column 58 failed at a load of 365,000 pounds, or 2,122 lbs./in.², and column 59 at 525,000 pounds, or 3,050 lbs./in.².

Examination of the gypsum after cooling indicated that the shrinkage of the material is such that it can not be expected to stay in place without ties of some kind after dehydration has progressed through, or nearly through, its thickness.

The columns given in Table 8 were made in gypsum forms 15 $\frac{7}{8}$ inches in internal diameter, 20 $\frac{3}{16}$ inches in external diameter by 21 inches long. The form sections for column 60 were made like those for 58 and 59 without fiber or other binder.

In the fire test of column 60 the cracking started in the first few minutes of the test, as in the tests of 58 and 59. A large piece of the gypsum covering fell off after 1 hour and 20 minutes of firing, and the entire covering with the exception of the top section, which was only partially exposed, had fallen within a few minutes, leaving the column practically uncovered after 1 hour and 40 minutes of firing.

The sections for the form of column 61 had already been cast before 60 was tested. In order to determine what results would be given by such protection if it could be kept in place, a large number of holes, each $\frac{7}{16}$ inch in diameter, were bored through the form sections for 61, in each of which a wire loop was inserted, with its ends extending into the space to be filled with concrete. When the concrete was cast, the holes filled at least partially with fine concrete, forming a system of reinforced concrete pegs projecting into the gypsum form. The gypsum covering cracked in this fire test very much as in the tests of the columns in gypsum forms already described. In this case, however, the gypsum covering supported by the concrete pegs stayed in place until the

test had been in progress for approximately 3 hours and 45 minutes, at which time it fell off rapidly, exposing the concrete, which immediately began to pop and snap violently.

In considering the apparent discrepancy between the temperatures recorded for this column and the somewhat low strength at the end of the four-hour fire test, some allowance should be made for the fact that the temperatures were measured in the vertical steel and not in the spiral, and that a few minutes were required to make the load test after the fire test was completed. Since the gypsum covering fell off in the test of column 61, 15 minutes before the end of the test, the spiral steel on this column was undoubtedly at a much higher temperature when the load test was finished than that indicated in the vertical steel at the end of the fire test.

One of the form sections for column 68 was made from potter's plaster instead of second-settle gypsum. All the sections for the column form were reinforced with a very light grade of expanded metal, the same as that used in the protective plaster on columns 4, 6, and 19. The expanded metal was formed into the shape of a cylinder which was placed in the mold before casting the section. In some of the sections the expanded metal cylinder was made of such diameter that it would be located near the inside of the form section. In others it was located about the middle of the thickness of the gypsum.

In the fire test a little spalling was observed in the first few minutes of the test. It was not of sufficient extent to be important. The characteristic checking began as usual after approximately 20 minutes of firing. At the end of 35 minutes long, regular cracks, some vertical and some diagonal, were observed. The checking, such as has been referred to several times, was of much smaller "mesh" in the section made from potter's plaster than in those made from second-settle gypsum. All the cracks increased greatly in width and in apparent depth during the remainder of the test. At the end of the four-hour test all the gypsum was apparently still in place, but parts of the covering were considerably out of shape from bulging or sagging (fig. 13).

When the column was examined after cooling, some of the gypsum was found to have fallen off. So far as could be judged by the apparent condition, there was no choice between the section made from potter's plaster and those made from second-settle gypsum. The expanded metal where located near the middle of the thickness of the gypsum was oxidized practically through.

Where it was located close to the inside it was in good condition, and there was sufficient strength left in the gypsum to afford fairly good anchorage.

A light 2-inch mesh poultry netting was used in the form sections for column 69. In all the sections the poultry netting was located close to the inner surface of the form. In the fire test there was nothing observed that calls for special mention, the checking and cracking being very similar to that observed in the test of 68. At the end of the four-hour fire test the gypsum was all in place on that part of the column which was visible. The poultry netting was found spaced from nothing to three-fourths inch from the inner surface of the form. It was in fairly good condition and holding sufficiently well.

For some reason the gypsum seemed firmer and in much better condition after this test than after that of 68. The material had shrunk from a thickness of $2\frac{5}{8}$ inches to approximately $1\frac{3}{4}$ inches. The outer portion, approximately one-fourth inch in thickness, was soft and friable and of a gray color. The next inch was of a buff color and fairly hard and strong. The inner one-fourth inch was white and soft. The furnace atmosphere had been slightly reducing most of the time, and the smell of sulphur in the air of the furnace room had been noticeable.

Microscopic examination of the material showed that the outer gray portion, approximately one-fourth inch in thickness, had been reduced to anhydrous calcium sulphate. The middle portion was mainly anhydrous, but apparently had not been heated sufficiently for the change to be complete. The inner, soft, white portion, approximately one-fourth inch in thickness, may have been in the form of plaster of Paris or may have been in the very beginning of anhydrous crystallization. Tested by the White method, the outer gray portion was found to contain free lime. It was also observed to air slake.

Column 69 after the four-hour fire test and a load test while hot up to 600,000 pounds (3,480 lbs./in.²) was apparently in good condition after being stripped of the gypsum covering and was plastered with a cement-cinder plaster and tested again as column 69a, which has already been described.

Attention may be called to the fact that column 70, cast in a gypsum form and tested without fire test, gave a higher test result in the strength test than any of the other gravel concrete columns tested (Tables 1 and 9). Inasmuch as only one column of this type was tested without fire test, no definite conclusion can be

drawn, but the strength of this column suggests the thought that the concrete may have developed greater strength because of the supply of water stored in the gypsum form.

The method of casting concrete columns in precast forms is not new. Columns have been cast in large construction work in forms cast from cinder concrete. Although the forms were not costly, the use of this method was found to add to the cost of the construction, and it has not come into common use. If it should become common practice in course of time to employ special safeguards against fire damage in structures built from the kinds of concrete which now appear to require them, it may be that the use of precast forms would be practical in some cases. Cinder concrete and other kinds of concrete which do not spall easily, while not having heat retarding properties equal to those of the gypsum, would have advantages in other respects and should be given thorough consideration in case the use of precast forms is contemplated.

XI. COLUMNS WITH 1½ INCHES OF PROTECTIVE CONCRETE, WITH SECONDARY REINFORCEMENT

In the earlier part of the investigation a light grade of expanded metal was used in protective plaster to insure its remaining in place during the first test. Use was also made of this material, as well as poultry netting, to hold gypsum protection in place, and it was a short step to the experimental use of the light expanded metal in the protective concrete of columns made from a spalling aggregate. This was tried in columns with 1½ inches and others with 2½ inches of protective concrete.

Since these columns were made at a considerably later date than similar columns without the secondary reinforcement that were made in the early part of the work, and since variables due to differences in the materials used, the consistency of the concrete, and the age at the time of test were to be avoided, a complete new series of 18-inch columns with spiral as well as vertical reinforcement, with Pittsburgh gravel aggregate, was made up, part of the series (columns 73, 74, and 75, Table 1) having plain protective concrete and 77 and 78 having secondary reinforcement or binder in the form of expanded metal in the outer concrete. The consistency of all these columns was made somewhat wetter than that of the early ones in order that the concrete might flow properly through the expanded metal and completely fill the form.

The test data for this series of columns are given in Table 1. The behavior of the ones without the secondary reinforcement

(73 and 74) in the fire test has been described in VII, 1 (a), with other columns of the same type. It is sufficient to state here that their behavior was similar to that of the earlier columns of the same type. In making columns 77 and 78 light, wide mesh expanded metal, such as was described in connection with the columns of Table 6 in Section XI of this report, was used as secondary reinforcement. One sheet of the expanded metal was bent and tied in cylindrical form, with the greater length of the diamonds running lengthwise of the cylinder, and this was placed in the form. No great care was taken to secure accuracy in the placing of the expanded metal, but it occupied a position between the spiral and the form. The concrete was placed as in other columns and poled moderately during the pouring. No difficulty was experienced in getting the concrete to fill out well in columns made in this way.

In the fire test of column 77 evidence of shell failure was observed at the end of 20 minutes, and the cracking and shattering of the outer concrete progressed steadily during the first two hours of the test. Very little change was observed during the remainder of the test in that portion of the column which was visible. During the latter part of the test a slab approximately 10 inches in diameter was observed to be standing out from the rest of the column on the visible side, and after the column had cooled a slab was found to have formed on the side which was not in sight during the test, and the top of this slab was standing out several inches from its original position, exposing the spiral which was visibly oxidized over an area of approximately one-half square foot. Where this slab had separated at its top, the expanded metal was oxidized clear through, freeing this portion of the slab. On another portion of the column, where the expanded metal was located within about one-fourth inch of the surface, it was found to be oxidized nearly through, leaving only a fine metal core in the center. In another portion where the expanded metal came within about one-fourth inch of the surface of the concrete it was not oxidized so nearly through.

Column 78 behaved much like 77 in the fire test, except that in this case no slabs separated from the column to such an extent as to expose the spiral reinforcement. Both of these columns made much better test records than similar columns without the secondary reinforcement, but distinctly poorer records than all columns of the same type that were made from nonspalling aggregates, although none of the latter had any metallic binder in the protective concrete.

XII. COLUMNS WITH 2½ INCHES OF PROTECTIVE CONCRETE, WITH AND WITHOUT SECONDARY REINFORCEMENT

It has been seen from the data given in Table 1 that 1½ inches of protective concrete made from highly siliceous gravel does not give fully satisfactory results. The protection was much better in the case of columns which had secondary reinforcement, in the shape of light expanded metal in the protective concrete, than in those columns made in the usual way, without anything to hold the protective concrete in place. It is obvious, however, from the test results that the protection was not sufficient to put concrete columns made from the unfavorable aggregates on a par with those made from what may be termed the nonspalling aggregates, and it should especially be noted that temperatures higher than 600° C. were reached in the reinforcement of these columns (77 and 78, Table 1). This is too high a temperature for both the steel and the concrete of all columns, and it is particularly bad for columns made from an aggregate high in quartz. It was considered desirable, therefore, to determine what would be gained by simply providing a greater thickness of protective concrete over columns made from the spalling aggregate and how much the results so obtained would be improved by the use of secondary reinforcement such as was used in columns 77 and 78. The columns given in Table 9 were accordingly made.

TABLE 9.—Columns With 2½ Inches of Protective Concrete

[Outside diameter, 20 inches; thickness of protective concrete, 2½ inches. Reinforcement: 2 per cent vertical, 8 round rods, ¾ inch diameter; 1 per cent spiral, ⅜ inch diameter, 2-inch pitch, 2 spacers. Effective area of concrete, 168.7 square inches; area of vertical steel, 3.53 square inches; effective area of column, 172 square inches; working load, 822 lbs./in.²]

Aggregates	Column number	Age at time of test		Stress at maximum load—			Maximum temperature at end of fire test at depth of vertical rods
		Months	Days	Without fire test	At end of four-hour fire test	Tested cold after four-hour fire test	
				Lbs./in.²	Lbs./in.²	Lbs./in.²	° C.
Pittsburgh gravel and sand	179	4	3	-----	1,495	-----	1,000
	180	4	1	-----	1,640	-----	960
	181	4	23	5,590	-----	-----	410
	282	4	3	-----	-----	5,115	470
	283	4	0	-----	-----	4,950	-----
	284	4	11	5,155	-----	-----	-----

¹ Columns Nos. 79, 80, and 81 had no metallic binder or reinforcement in the protective concrete.

² Columns 82, 83, and 84 had a light wide mesh expanded metal in the protective concrete.

As is apparent from the test results given in the table, the protection afforded by $2\frac{1}{2}$ inches of concrete without secondary reinforcement, while somewhat more effective than that of $1\frac{1}{2}$ inches of the same kind of concrete without secondary reinforcement, was much less effective than that of $1\frac{1}{2}$ inches of concrete with secondary reinforcement. The behavior of column 79 and that of 80 in the fire test were so nearly alike that the account of the observations made in the test of 79 will serve for both.

Shell failure was in evidence after 25 minutes of firing. The outer portion of the concrete broke up rapidly, and at the end of 34 minutes a slab about $2\frac{1}{2}$ feet long had fallen off. So far as could be judged, the average thickness of this slab was rather small, apparently about 1 inch. The protective concrete continued to break up and fall off. The outer portion came first in rather thin slabs, but the action continued, the freshly exposed concrete breaking up and falling off in its turn. After 2 hours and 13 minutes steel was exposed to an important extent. (In the test of column 80 the steel was exposed over a considerable area after 1 hour and 49 minutes.)

After three hours it was observed that the portion of the protective concrete which was still in place was continuing to break up. It was impossible to tell what proportion of the material had come off, but it was estimated that more than half of it was in place on that portion of the column which was visible from the observation holes. All the concrete visible was very much broken up.

It is evident from this account that while these columns did not lose their protection as rapidly or as completely as those given in Table 1, which differed from them only in the thickness of the protective concrete, they did lose it to such extent as not to give fully satisfactory results.

In columns 82, 83, and 84 the light grade of expanded metal, which was described more in detail in connection with columns with additional insulating material in the form of plaster, Section IX of this report, was used. A sheet of expanded metal of proper size was bent into the form of a cylinder with the greater length of the meshes running lengthwise of the cylinder and fastened by wiring in position approximately midway between the column reinforcement proper and the form. Concrete was placed in the usual way and poled moderately during pouring.

In the fire tests of columns 82 and 83 cracking began earlier with 82 than with 83 and was somewhat more extensive. It may be stated briefly that cracks appeared in the concrete in both

FIG. 13.—Views of specially protected columns (68, 80, and 82) after failure when load was increased following the four-hour fire test

tests, and that they were generally vertical. The concrete did not break up into slabs, as in the case of columns which did not have the secondary reinforcement, and none of it fell off during the fire and only minor spalls in the subsequent loading (fig. 13). The cracks, while giving evidence of the tendency of the concrete to spall if not restrained, can not be considered important so far as the protection afforded these columns is concerned. As shown by Table 9, these columns both withstood the load of 3,480 lbs./in.² while hot at the end of the four-hour fire test. When the columns were examined after cooling, it was found that the protective concrete was very much shattered throughout its thickness.

FIG. 14.—Furnace and column temperatures, 20-inch Pittsburgh gravel concrete column No. 83, with expanded metal in the $2\frac{1}{2}$ -inch thickness of protective concrete

In considering the possibilities of this method of protection it may be suggested that it would involve less of a departure from usual construction practice than any of the others that have been tried out in this investigation. The results indicate that it would be entirely reliable. The thickness of protective concrete used in a given building would be governed by the class of building, which in turn is determined largely by the occupancy for which it is intended. It would not be far wrong to say that, in general, the thickness of protective concrete should be the same with concrete of the spalling type requiring the secondary reinforcement as with concretes in the nonspalling class which do not require the secondary reinforcement.

XIII. DISCUSSION OF TEST RESULTS

1. TEST RESULTS OBTAINED WITH COLUMNS OF DIFFERENT TYPES

The early part of the work showed a great difference in the fire resistance of columns made from two distinct classes of aggregates. This difference was shown in the three common types of columns tested—round columns with hooping, round columns without hooping, and square columns without hooping—all having the same amount of vertical reinforcement. The aggregates included can be classified according to whether the concrete produced has a tendency to spall in fire tests. Three types of gravel showed a decided spalling tendency and the other aggregates included in the work, viz, crushed limestone, limestone gravel, trap rock, and blast-furnace slag, did not show it at all.

(a) **ROUND HOOPED COLUMNS.**—As shown in Table 1, eight of the nine columns of this type made from Pittsburgh gravel, pure quartz gravel, and from Long Island gravel failed under the working load before the end of the four-hour fire test. The ninth column of this type failed at the end of the four-hour fire test at a load which was less than 20 per cent of the ultimate strength of a similar column which had not been fire tested. The average ultimate strength in the heated condition at the end of the four-hour fire test of the columns of the same type but made with nonspalling aggregates, was more than 50 per cent of that of similar columns that had not been fire tested. Those made from limestone gravel and from crushed limestone did not fail in any case when the load was increased at the end of the fire test up to the capacity of the furnace-loading equipment, which is equivalent to 3,480 lbs./in.² for these columns. When tested cold within 30 days after the fire test, these limestone gravel columns and crushed limestone columns showed an average ultimate strength approximately 80 per cent as high as that of similar columns that had not been fire tested.

The apparent cause of the great difference between the fire resistance of the columns made from spalling aggregates and those made from nonspalling aggregates was the loss of the protective concrete by the columns with the spalling aggregates. The protective concrete commenced to crack early in the fire test and then to break up into slabs and fall off, so that after approximately one hour of firing the steel and load-bearing concrete would begin to be exposed, and the exposed area would increase in extent so that

during the latter half of the test the column would have little or no protection. The temperature data of Tables 1 and 10 show the effect of this loss of protective covering on the temperature progress in the steel and the load-bearing concrete.

TABLE 10.—Temperature Data from 18-Inch Round Columns

	Column number	Age at time of test		Temperatures at depth of vertical rod (centers of rods $2\frac{1}{8}$ inches from surface of columns)				Temperatures at point midway between center of vertical rod and center of column ($5\frac{3}{8}$ inches from surface of column)				Temperatures at center of column			
		Months	Days	1 hour	2 hours	3 hours	4 hours	1 hour	2 hours	3 hours	4 hours	1 hour	2 hours	3 hours	4 hours
				° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.
Gravel concrete columns not greatly affected by spalling.	8	7	19	165	350	507	610	100	100	175	260	50	80	90	130
	9	9	11	185	385	515	625	100	120	200	310	70	100	110	180
	77	4	3	110	300	495	650								
	78	4	0	100	245	425	555								
Gravel concrete columns greatly affected by spalling.	1	6	4	346	682	840	1,937	65	145	305	1,390	30	90	130	230
	2	6	7	275	805	972	1,035	75	160	320	445	30	110	140	290
	3	7	9	130	620	812	900	40	100	207	340	20	100	100	210
	43	4	7	140	735	985	(²)	70	145	300	(²)	60	90	150	(²)
	46	4	3	120	410	855	³ 950	45	90	160	³ 250	30	80	90	³ 100
	47	4	5	160	470	825	⁴ 960	50	100	165	⁴ 250	30	80	100	⁴ 100
	73	4	0	110	700	900	980								
	74	4	0	125	425	715	⁵ 780								
Limestone concrete columns.	17	7	1	110	285	410	485	35	100	130	215	10	50	110	110
	18	8	17	200	370	465	530	30	85	105	180	10	50	110	---
	21	7	7	180	390	490	570								
	22	7	2	190	375	490	570	100	100	125	215	50	100	100	100
Blastfurnace slag concrete.	48	4	0	110	260	370	430	60	85	85	85	50	85	85	85
	50	4	21	95	210	370	---	20	50	100	100	10	50	50	95
Trap rock concrete.	54	4	7	135	330	470	590	40	75	100	185	20	25	80	100
	55	4	16	125	310	440	530	40	100	130	215	20	50	110	110
Limestone gravel concrete.	85	4	1	110	255	380	460								
Gravel concrete columns in which 1 inch or more of the protective material was plaster:	86	4	1	170	270	385	465								
Plaster of Portland cement and sand (considerable portions of plaster fell off during fire test in all cases).	63	9	17	80	255	430	580	30	85	105	170	10	80	90	90
	66	4	4	125	430	630	750	50	105	220	325	20	95	---	150
	71	4	0	120	275	450	570	50	100	145	230	30	100	---	---
	72	4	0	230	480	635	730								
Plaster of cement and crushed cinders.	⁶ 69a	---	---	115	280	425	520	80	100	145	230	25	95	95	115
Plaster of Portland cement, asbestos, and sand.	65	4	26	110	230	335	420	55	100	130	185	35	85	100	100
	88	4	1	150	290	405	505								
Plaster of gypsum, lime hydrate, and kieselguhr with wire binder.	67	4	22	65	85	130	180	35	55	75	95	20	40	75	95

¹ Final temperatures for column 1 read at 3 hours and 40 minutes because of failure of column.

² Final temperatures for column 43 read at 3 hours and 00 minutes because of failure of column.

³ Final temperatures for column 46 read at 3 hours and 30 minutes because of failure of column.

⁴ Final temperatures for column 47 read at 3 hours and 40 minutes because of failure of column.

⁵ Final temperatures for column 74 read at 3 hours and 20 minutes because of failure of column.

⁶ See note to Table 7.

It appeared from the observations made during the tests that the failure of the outer concrete of these columns was due to the

rapid expansion of this portion of the column while the inner portion was still comparatively cold. As stated in other paragraphs, the fact that this takes place with columns made from one type of aggregate and not with those made from another type appears to be due to difference in expansion of different minerals at high temperatures. The fact that the loss of protective concrete was more rapid and more extensive in the case of hooped columns than with either round or square columns without hooping may be due, in part, to the greater load carried by the hooped columns in the fire test, but it seems probable that it was due in larger measure to the opportunity for definite division or parting interposed between the protective concrete and the concrete of the column proper presented by the hooping. A summary of temperatures attained in 18-inch round columns with and without hooping is given in Table 10.

(b) **ROUND COLUMNS WITHOUT HOOPING.**—In columns of this type from limestone aggregate the strength at the end of the four-hour fire test was approximately 50 per cent of that of a similar column not fire tested, whereas the columns made with gravels of spalling types had only a little over half of this strength. This is explained, in part, by the fact that the latter columns lost portions of the protective concrete in the course of the fire test (Table 2).

(c) **SQUARE COLUMNS WITHOUT HOOPING.**—There was no spalling from square columns made from what have been termed nonspalling aggregates—limestone, blast-furnace slag, and trap rock. The outer concrete of columns made from two types of siliceous gravels spalled and shattered badly. Spalling took place more rapidly in the square columns than in round ones with vertical reinforcement without hooping, but was not as destructive as in spirally reinforced columns. In the fire tests of square columns made from spalling aggregates there was a decided tendency for the portion of the corners of the column outside of the vertical rods to split off or split loose and in course of time to fall away from the column. In the latter part of the test deep cracks, approximately vertical, opened in the sides of the columns. While the spalling was more rapid and destructive in the square columns made from spalling aggregates than in round ones without spiral, the fact that these square columns gave somewhat better results than the corresponding round, spirally reinforced columns should not be lost sight of. The proportionate loss of strength in the fire test was approximately the same in square columns with limestone aggregate as in round ones without spiral reinforce-

ment. Square columns made from blast-furnace slag and from trap rock were somewhat lower in ultimate strength at the end of the fire test than those with limestone aggregate. This may have been due, in part, to the fact that the limestone columns were tested at a greater age than the others. The temperatures attained in the square columns are given in Table 11.

TABLE 11.—Temperature Data from 16-Inch Square Columns

	Col- umn num- ber	Age at time of test		Average of temperatures of two vertical rods (centers of rods 2 1/8 inches from surface of column)				Temperature at center of column			
		Months	Days	1 hour	2 hours	3 hours	4 hours	1 hour	2 hours	3 hours	4 hours
				° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.
Gravel concrete not greatly affected by spalling.....	25	7	24	250	485	640	750	80	100	100	150
Gravel concrete affected by spalling.....	44	4	8	260	780	985	1,000	90	105	110	250
	45	4	24	235	570	780	900	95	-----	165	280
Limestone concrete ¹	29	8	14	175	420	550	630	0	70	100	100
	30	8	27	210	425	550	630	0	80	90	100
Blast-furnace-slag concrete	51	4	5	150	385	560	680	25	50	90	100
	53	4	12	140	370	570	690	-----	-----	-----	-----
Trap-rock concrete.....	56	4	5	160	390	560	670	-----	-----	-----	-----

¹ Tests made after extremely cold weather.

2. CAUSE OF SPALLING

The fact that concrete columns made from some aggregates have a strong tendency to spall in fire tests and those made from other aggregates do not exhibit this tendency is traceable to the fact that certain minerals expand slowly and gradually when heated, whereas others expand gradually up to a certain point and then undergo a sudden volume increase of relatively great magnitude. Data are available to show that diabase, for example, which is the prevailing mineral constituent of trap rock, a nonspalling aggregate, expands gradually through the temperature range encountered in fire tests, whereas quartz and granite, one or both of which are major constituents of the spalling aggregates included in this investigation, expand gradually up to a temperature of approximately 575° C. (1,067° F.) and then show a large and sudden expansion. The total expansion of diabase up to 1,000° C. is less than that of quartz and the granites up to 600° C.⁵ It seems probable that the relatively high expansion of such aggregates is accountable for the spalling tendency of concrete made from them.

⁵ Day, Sosman, and Hostetler, *Am. Jour. Sci.*, 37, p. 1; 1914.

3. PREVENTION OF FAILURES DUE TO SPALLING

In many localities it would be too expensive to use nonspalling aggregates, and it was considered advisable to include in this investigation several series of columns protected by materials other than the plain protective concrete now universally provided.

(a) COLUMNS PLASTERED OVER THE PROTECTIVE CONCRETE.—Three 18-inch hooped columns, two made from Pittsburgh gravel and one from limestone, were plastered with 1 inch of cement-lime-sand plaster. Light expanded metal was provided in the plaster to insure its staying in place in the fire test. As shown in Table 6, this protection was so effective that there is no evidence in the test results that the ultimate strength of these columns was not as high after the fire test as before. It will be noted that the maximum temperatures attained in the steel were only slightly higher than 400° C.

(b) COLUMNS PROTECTED BY PLASTER IN THE PLACE OF PROTECTIVE CONCRETE.—The substitution of plaster for protective concrete was tried in the 10 columns on which data is given in Table 7. These were round columns with vertical and spiral reinforcement. In some cases the columns were cast in 16-inch diameter forms instead of 18-inch diameter and the additional 1-inch thickness of protective material put on in the form of plaster. In some cases the reinforcement was covered with metal lath before the column was poured, and this served as the form for the column, which was afterwards plastered. In other cases the protective plaster was applied on the metal lath before the column was poured. In all cases these columns gave better results in the fire test than similar columns with plain concrete protection. On the other hand, none of those plastered with cement-lime-sand plaster without binder gave fully satisfactory results. This is attributable in a measure to the fact that portions of the plaster fell off these columns in the course of the fire test, usually in the early part.

Two columns (65 and 88) which were plastered with a special plaster containing an asbestos compound gave good results, one of them exceptionally so. This plaster did not separate and fall off in the fire test and gave good thermal protection.

One column (69a), which had been fire tested before, was covered with plaster made from Portland cement and crushed bituminous cinders. In this case the cement-cinders plaster stayed in place in the fire test and gave good results.

One column (67) was covered with a special insulating plaster of gypsum, lime, and kieselguhr. Poultry netting was used as a binder in the plaster. The temperatures attained in the column (Table 10) were remarkably low, and the strength after the fire test was so high as to make it doubtful whether the column suffered any structural deterioration in the fire test. The thickness of the plaster was 1 inch, and the total thickness of protective material was $1\frac{1}{2}$ inches.

(c) COLUMNS CAST IN GYPSUM FORMS.—Data from the tests of these columns are given in Tables 8 and 12. The columns were cast in forms built up in sections from hollow cylinders, $2\frac{5}{8}$ inches thick, made of gypsum. It was found that, on account of its dehydration and attendant shrinkage, the gypsum covering would not stay in place through a four-hour fire test unless some sort of reinforcement or binder were provided to hold it. With light expanded metal or poultry netting cast in the gypsum, the protection afforded was good, and the columns showed satisfactory strength at the end of the fire test and after cooling.

TABLE 12.—Temperature Data from Pittsburgh Gravel Concrete Columns Cast in Gypsum Forms With Metal Binder

Column number	Age at time of test		Average of temperatures of two vertical rods (centers of rods $3\frac{1}{4}$ inches from surface of form)				Average of temperatures of two points midway between center of vertical rod and center of column ($5\frac{1}{8}$ inches from surface of form)				Temperature at center of column			
	Months	Days	1 hour	2 hours	3 hours	4 hours	1 hour	2 hours	3 hours	4 hours	1 hour	2 hours	3 hours	4 hours
68.....	4		° C. 45	° C. 75	° C. 100	° C. 255	° C. 25	° C. 50	° C. 70	° C. 90	° C. 25	° C. 40	° C. 60	° C. 85
69.....	4	2	45	65	85	175	25	55	65	90	20	40	60	90

(d) COLUMNS WITH $2\frac{1}{2}$ -INCH PLAIN CONCRETE PROTECTION.—These columns were tested to determine the effectiveness of relatively thick coverings of plain protective concrete in the case of columns made from aggregates in the spalling class. As shown by the test results of Tables 9 and 13, the fire resistance of these columns (79 and 80) was distinctly better than that of columns of the same general type with the same aggregate, but with only $1\frac{1}{2}$ inches of plain protective concrete. On the other hand, it was distinctly inferior to that of columns with nonspalling aggregate and only $1\frac{1}{2}$ inches of plain protective concrete. The fire resistance was also inferior to that of similar columns with spalling

aggregate and $1\frac{1}{2}$ inches of protective concrete with secondary reinforcement or binder of light expanded metal in the protective concrete (columns 77 and 78). The columns with $2\frac{1}{2}$ inches of plain protective concrete did not lose this protective covering as rapidly or as extensively as similar columns with $1\frac{1}{2}$ -inch plain concrete coverings, but the results can not be regarded as satisfactory.

TABLE 13.—Temperature Data from 20-Inch Round Columns with $2\frac{1}{2}$ Inches of Protective Material

	Column number	Age at time of test		Average of temperatures of two vertical rods (centers of rods $3\frac{1}{8}$ inches from surface of column)				Average of temperatures of two points midway between center of vertical rod and center of column ($6\frac{1}{8}$ inches from surface of column)				Temperatures at center of column			
		Months	Days	1 hour	2 hours	3 hours	4 hours	1 hour	2 hours	3 hours	4 hours	1 hour	2 hours	3 hours	4 hours
				° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.
Columns greatly affected by spalling: Gravel concrete columns with plain concrete outside the steel.....	79	4	3	90	280	795	960	-----	-----	-----	-----	-----	-----	-----	-----
	80	4	1	80	460	700	805	-----	-----	-----	-----	-----	-----	-----	-----
Columns not greatly affected by spalling: Expanded metal in protective concrete.....	82	4	3	90	145	270	400	-----	-----	-----	-----	-----	-----	-----	-----
	83	4	-----	80	150	295	445	-----	-----	-----	-----	-----	-----	-----	-----
Columns originally 18 inches in diameter with the added protection of 1 inch of Portland cement plaster which was reinforced with light expanded metal.....	4	12	2	85	185	265	355	20	85	105	140	0	55	90	90
	6	5	16	120	190	290	370	55	105	115	155	50	80	105	110
	19	10	23	110	165	290	390	25	80	90	130	10	40	85	90

(e) COLUMNS WITH LIGHT EXPANDED METAL IN THE PROTECTIVE CONCRETE.—Secondary reinforcement of binder in the outer concrete was tried in columns made from Pittsburgh gravel with $1\frac{1}{2}$ -inch protective concrete (77 and 78) and in columns with $2\frac{1}{2}$ -inch protective concrete (82, 83, and 84). The $1\frac{1}{2}$ inches of protective concrete with binder gave much better results than similar columns without the binder, but not as good as similar columns with nonspalling aggregates and no secondary reinforcement. The fire tests of columns with $2\frac{1}{2}$ -inch protection with binder gave satisfactory results, the protective concrete all staying in place during the fire test and the ultimate strength of the columns being approximately the same after the fire test as for columns not subjected to the fire test.

4. EFFECT OF THE FIRE ON ELASTIC PROPERTIES

The length of time the columns withstood the fire tests under working load and the additional load sustained at the end of the fire test or subsequent to cooling give information on the load-carrying capacity of the columns during the fire and subsequent to cooling. As a further aid in determining the feasibility of reuse of columns in buildings after exposure to fire, information on the effect of the fire on the stress-deformation ratio or modulus of elasticity is desirable.

In Figures 15 and 16 are given typical deformation curves for columns not fire tested and for columns tested cold after subjection to the four-hour fire test under working load and at its conclusion the full load of the furnace equipment (3,480 lbs./in.²). It is seen that the unit deformation on reloading after fire test and load test in the hot condition is between two and three times larger than with comparable columns on first loading without fire test, the modulus of elasticity being correspondingly lower. This can be considered as due to the effect of the fire on the concrete, particularly on that in the outer portion of the column and in part to the previous load test. The increase in unit deformation for a given unit load while large can not be considered as prejudicial to reuse after fire. Under a load of 1,000 lbs./in.² the difference in deformation between a column previously subjected to fire and one loaded without previous fire test is about 0.025 inch per 10-foot height, a difference that the framing can be considered capable of absorbing even if more than one building story is involved.

For the columns that failed in the fire test or in the loading at the end of the fire test no deformation or strength data for the cooled condition after fire test were obtainable. The effect of the fire was without doubt more marked than for the columns that withstood the fire and excess load in the heated condition, but it appears doubtful that the resulting deformation characteristics of the concrete would preclude reuse if adequate factors of safety on strength were present. The cold-drawn spiral reinforcing steel would suffer a large lowering in yield point and ultimate strength if temperatures high enough to anneal the steel are attained in the fire exposure, although still retaining the strength and elastic properties of mild or medium steel. The rolled vertical reinforcing bars would be affected to much smaller extent from the same cause. This would lower the ultimate strength of laterally reinforced

FIG. 15.—Deformation curves for Pittsburgh gravel concrete columns Nos. 4, 5, and 6

FIG. 16.—Deformation curves for limestone concrete columns Nos. 18, 19, and 20

columns, although deformation under the lower loads would not be greatly affected by the change in the properties of the steel, the annealing causing only minor changes in its modulus of elasticity.

XIV. SUMMARY

1. COMPARATIVE PERFORMANCE WITH DIFFERENT AGGREGATES

The results of this investigation give strong confirmation to the conclusion that the tendency of concrete made from certain types of aggregate to spall in fire tests and in fires in buildings is due to the expansion properties of certain mineral constituents which predominate in those aggregates. The expansion behavior of quartz and of granites when heated to temperatures as high as the inversion point of quartz, 573.3°C . ($1,064^{\circ}\text{F}$.) are such as to render concrete containing large proportions of either or both of these classes of minerals especially susceptible to damage by fire.

2. EFFECTS FROM SHAPE, DESIGN, AND SIZE OF COLUMNS

It has been shown by this work that round columns are not necessarily superior to square ones in point of fire resistance. In columns made from nonspalling aggregates, such as limestone, blast-furnace slag, and trap rock, the results do not indicate any advantage of one form over the other. The least favorable results were those from fire tests of round columns with both longitudinal and spiral reinforcement and made from spalling aggregates, including Pittsburgh gravel and two other types of gravel, one very high in quartz content and the other containing large proportions of quartz and granite. The round-hooped column proved to be particularly susceptible to fire damage, except when made with concrete in which the aggregate was of the nonspalling type. On the other hand, round columns without hooping but with spalling aggregates gave somewhat better results than square columns of the same type. If columns are made from concrete with a nonspalling aggregate there is no advantage, in point of fire resistance, in the round over the square column. In the case of spalling aggregates, the fire resistance problem can not be solved by the use of round instead of square columns, and this applies particularly to hooped columns.

The tests with plain concrete columns indicate that from the standpoint of safety during the fire they are as safe under their working load as the reinforced columns are under the higher

working load allowed for the different types, although where made with aggregates of the spalling type light metal reinforcement and ties in the outer protection are highly desirable.

In the matter of size of column the results indicate decrease in resistance with decrease in size, although with the same thickness of protection the higher ratio of concrete considered as protection to that considered as load bearing helps to reduce the actual unit stress imposed in the case of the smaller columns, except for hooped columns made with siliceous aggregates, where the disruption and spalling of the protective concrete left the load supported on the unprotected column core.

3. PROTECTION TO PREVENT MATERIAL FIRE DAMAGE

It has been demonstrated that concrete columns require the protection of heat-insulating material of some kind, just as steel columns do, although failure of unprotected concrete columns on exposure to fire is not as imminent because of the lower conductivity of the material. In case where spalling aggregates are used, plain concrete covering the steel is not an efficient protective material. Either the protective concrete should be provided with light metallic reinforcement to prevent its dislodgment or some other material should be substituted for it. On the other hand, plain concrete covering the steel has been shown to be efficient and satisfactory as protective material if made from an aggregate in the nonspalling class.

The evidence of the fire-test results indicates that in columns made from spalling aggregates the expansion stresses in the load-bearing portion of the column contribute to the loss in strength more than in columns made from nonspalling aggregates if temperatures as high as 575° C. or over are attained in the load-bearing concrete. In other words, the expansion behavior, which has a tendency to produce spalling, may weaken the column even though no spalling actually occurs. However, it seems necessary if appreciable fire damage is to be prevented to insulate columns and other structural members well enough to prevent the steel and load-bearing concrete from reaching these temperatures whether the aggregate used be of a spalling or nonspalling type. Judging from the results of this investigation, concrete made from a spalling aggregate may be as nearly immune to fire damage as that made from a nonspalling aggregate provided it is so protected that the temperatures in the steel and load-bearing concrete will be kept

reasonably low—say, below 500° C. (932° F.)—which appears feasible where necessary or desired. The problem of providing the necessary insulation is, of course, simpler when a nonspalling aggregate is used.

4. PROTECTION TO PREVENT FAILURE UNDER WORKING LOAD

The most important function of columns in buildings subjected to fire is to support load, and thereby prevent local or general collapse that would endanger life of occupants and firemen and aid the spread of fire within the building and to adjacent buildings. Reinforced concrete buildings as a type present desirable general fire-resistive characteristics in being incombustible and not subject to immediate collapse on exposure to fire. It is shown in these tests that while there is a wide range in the fire resistance of concrete columns, depending mainly on the mineral constituents of the aggregates employed or the method of protecting the load-bearing portion, even the less favorable results obtained indicate an inherent fire resistance that must be recognized when the main concern is the ability to function satisfactorily as load-bearing members in fires of the intensity and duration to which buildings of a given type and housing given occupancies may be subjected. This aspect of performance is the main concern of State and municipal regulation, whose police power is limited by considerations of public welfare and safety. Owners and others more directly interested may be concerned also with the damage, short of failure of function, that the fire inflicts and with the cost of restoration. Portions of the investigation were devoted to the development of means for reducing such fire effects to a minimum and show that this can be done, should be done in all cases when the exposure is severe, and is possibly a profitable thing to do under almost all conditions. The ability to come through fires without failure under working load does not imply freedom from damage to the load-bearing portion as well as to the protecting material. Such damage under exceptional conditions may be such as to render complete replacement or major repair necessary.

XV. FIRE-RESISTANCE PERIODS

The fire-resistance period is a convenient unit to which results of fire tests can be reduced and made available for use. It is derived from the results of tests, with suitable margins taken for variations in material, workmanship, design, and size of columns

obtaining in building construction to which the results may be applied but not obtaining in the relatively few test specimens and construction conditions that could be introduced. With safe units thus established and an estimate made of the duration of fires possible in a building of given type and occupancy, column types and protections can be chosen adequate for the conditions to be met.

1. METHOD OF DERIVATION

The fire-resistance periods are derived with main reference to ability to perform satisfactorily during the fire exposure as outlined in the preceding section. For columns that failed during the four-hour fire test or took only a small increment of load at its conclusion the safe fire-resistance period is taken as two-thirds of the average time to failure of a group of similar columns under the standard fire conditions of the tests, but not higher than four-fifths of the lowest resistance developed by any column within the group. Periods are taken at intervals of one-half hour up to four hours, an even value of the resistance period being taken if the computed value is not more than one-fourth of the interval below or three-fourths of the interval above the given period value.

For columns that withstood under working load the four-hour fire test the four-hour classification is given if the load sustained while hot at the end of the fire test is not less than 50 per cent of the strength of comparable columns not subjected to fire tests. For columns failing at the end of the four-hour fire test under lower loads corresponding reductions in the fire-resistance periods assigned them are made. For columns withstanding a greater load while hot at the end of the four-hour fire test the five-hour classification is given if the strength while hot is not less than 55 per cent of that of comparable columns not subjected to fire and not less than 70 per cent of such strength when tested cold after subjection to the maximum load of the furnace equipment (3,480 lbs./in.²) while hot. The six-hour classification is given if the strength while hot is not less than 55 per cent of that of similar columns not fire tested, and when tested cold after fire test not less than 80 per cent of the unfired cold strength. Periods over six hours are not significant since the six-hour standard fire exposure is considered more severe than the maximum fire exposure occurring in buildings under any but the most exceptional conditions.

The method of deriving the resistance periods has been chosen as most acceptable for the test conditions of this investigation and should not necessarily be taken as generally applicable to investigations where different test conditions are present.

2. TABLE OF FIRE-RESISTANCE PERIODS

The periods derived from the results of this investigation according to the method outlined above are given in Table 14. The resulting periods cover a range from one and one-half to six hours or over, depending mainly on the column size and type, concrete aggregates used, and thickness and type of protection. It is seen that for columns not smaller than 16 inches in outside diameter or 15 inches square a variation in safe-resistance period from two and one-half hours to six hours obtains, mainly from difference in mineral composition of the concrete aggregates employed. The siliceous aggregates with which the lower periods obtain are taken to have not less than 60 per cent of quartz, chert, or granite, and the calcareous aggregates with which the highest resistance obtains not more than 10 per cent of the same minerals. No definite information has up to the present been obtained on the fire resistance of concrete made with gravels and other aggregates containing siliceous material in amount intermediate between these limits, and no periods for concrete columns made with such aggregates are here given, although presumably they would be intermediate between those given for highly siliceous aggregates and those for calcareous aggregates. The trap rock and blast-furnace slag concrete is seen to occupy a position intermediate between concrete made with aggregates predominantly siliceous and calcareous.

The following periods indicate the effectiveness of adding secondary reinforcement in the concrete protection where siliceous aggregates are used, the resistance periods increasing from two and one-half hours without the reinforcement to three and one-half hours with the mesh or expanded metal in the 1½-inch protection and from three hours to six hours or more where reinforcement is added in the 2½-inch protection. It is seen that little is gained by increasing the thickness of protection without adding the secondary reinforcement. Six-hour resistance is obtained by adding 1 inch of reinforced plaster outside of the 1½ inches of concrete or by casting the column in reinforced gypsum forms 2 inches thick.

TABLE 14.—Fire-Resistance Periods of Concrete Columns

[Concrete mixture to be not leaner than 1 : 2 : 4 Portland cement, sand, and coarse aggregate, by volume.
Details of design and loading to conform with generally accepted standards]

Type of column	Shape	Minimum area of solid material	Coarse aggregate	Protection		Fire-resistance period
				Description	Thickness	
Plain concrete.....	Round..	Sq. in. 200	Sixty per cent or more quartz, chert, or granite.	Plain concrete, same as column.	Inches 1½	Hours 2½
Vertically reinforced.	Square..	200	do.....	do.....	1½	2½
Do.....	Round..	200	do.....	do.....	1½	3
Do.....	Round or square.	200	Trap rock or blast-furnace slag.	do.....	1½	3½
Do.....	do.....	200	Limestone or calcareous gravel; quartz, chert, or granite not more than 10 per cent.	do.....	1½	4
Laterally and vertically reinforced.	do.....	110	Sixty per cent or more quartz, chert, or granite.	do.....	1½	1½
Do.....	do.....	200	do.....	do.....	1½	2½
Do.....	do.....	200	Trap rock or blast-furnace slag.	do.....	1½	4
Do.....	do.....	200	Limestone or calcareous gravel; quartz, chert, or granite not more than 10 per cent.	do.....	1½	6
Do.....	do.....	200	Sixty per cent or more quartz, chert, or granite.	Concrete same as column reinforced with expanded metal or wire mesh.	1½	3½
Do.....	do.....	250	do.....	Plain concrete same as column.	2½	3
Do.....	do.....	250	do.....	Concrete same as columns reinforced with expanded metal or wire mesh.	2½	6
Do.....	do.....	250	do.....	One and one-half inches of plain concrete same as column covered with 1-inch Portland cement or gypsum plaster reinforced with expanded metal or wire mesh; plaster proportions not leaner than 1 : 2½ by volume with admixture of not over one-half part lime.	2½	6
Do.....	do.....	250	Limestone or calcareous gravel; quartz, chert, or granite not over 10 per cent.	do.....	2½	6
Do.....	do.....	250	Sixty per cent or more quartz, chert, or granite.	One-half inch of concrete same as column covered with a 2 inch thick unreinforced gypsum mold within which column is cast.	2½	3
Do.....	do.....	250	do.....	Same as above, except that gypsum mold is reinforced with expanded metal or wire mesh.	2½	6
Do.....	do.....	200	do.....	One-half inch of concrete same as column covered with 1-inch unreinforced Portland cement or gypsum plaster not leaner than 1 : 2½ by volume with admixture of not over one-half part lime; surface of column hacked or column cast in metal lath form.	1½	3

TABLE 14.—Fire-Resistance Periods of Concrete Columns—Continued

Type of column	Shape	Minimum area of solid material	Coarse aggregate	Protection		Fire-resistance period
				Description	Thickness	
Laterally and vertically reinforced.	Round or square.	Sq. in. 200	Sixty per cent or more quartz, chert, or granite.	One-half inch of concrete same as column covered with 1-inch unreinforced Portland cement-cinder plaster, 1:3 by volume; surface of column hacked or column cast in metal lath form.	Inches 1½	Hours 4
Do.	do.....	200	do.....	One-half inch of concrete same as column covered with 1 inch of unreinforced Portland cement asbestos and sand plaster of proportion 1:1½:2 by volume; surface of column hacked or column cast in metal lath form.	1½	5
Do.....	do.....	200	do.....	One-half inch of concrete same as column covered with 1 inch of gypsum hydrated lime kieselguhr plaster, of proportion 1:½:2 by volume, reinforced with 2-inch wire mesh or equivalent.	1½	6

All of these latter methods involve protections of 2½ inches total thickness, which may be objectionable under many conditions. The concluding part of the table gives periods for protections where the plaster replaces an equal thickness of protective concrete, thereby reducing the total thickness of the protection to 1½ inches. It is seen that only a minor gain is obtained by replacing 1 inch of siliceous gravel concrete with unreinforced Portland cement or gypsum plaster. Somewhat greater resistance is obtained with unreinforced cement-cinder plaster and cement-asbestos-sand plaster due to somewhat better insulating properties and greater ability to remain in place. The highest results were obtained with a reinforced gypsum-lime-kieselguhr plaster held in place by the wire mesh. Considerable gain in resistance would obtain with the other plasters if similarly reinforced.

3. COMPARISON WITH RESULTS OF OTHER INVESTIGATIONS

In the jointly conducted investigation of the fire resistance of building columns referred to on page 637, six reinforced concrete columns were included in the fire test series and three were

subjected to fire and water tests.⁶ The columns were round or square vertically reinforced and round spirally hooped and vertically reinforced, the concrete aggregates employed being trap rock and dolomitic limestone, except in the columns for the fire and water tests, portions of which were made with siliceous gravel concrete. All columns had a 2-inch protection of concrete the same as in the column, without reinforcement.

Two of the trap rock concrete columns withstood the standard fire test under working load for periods between seven and eight hours, and the third sustained a load at the end of the eight-hour fire test about 25 per cent in excess of the working load.⁷ The limestone concrete columns all withstood the eight-hour fire test under working load and at its conclusion, loads averaging two and one-fourth times the working loads. With both aggregates, little cracking and almost no spalling occurred during the fire test. In the one-hour fire test preceding the water application in the fire and water test the fire effects⁸ were very similar to those previously described in this paper, the trap rock and limestone concrete being little affected, while the siliceous gravel concrete cracked and spalled, exposing portions of the reinforcement in the case of the hooped column. The five-minute water application from a 1½-inch nozzle under 50 pounds pressure carried away the concrete damaged during the preceding fire exposure and some of the adjacent portions, the vertical bars of the square columns being quite generally exposed and the bars and spiral hooping in the portion made with siliceous aggregates in the case of the round columns. After cooling the columns sustained at failure loads averaging four times the design working load. The condition of the columns after the fire and water treatment was not such that they would be subject to early failure in case of a recurring fire, with the limitation on permissible percentages of reinforcement prescribed by current standards of practice. Recurring fires are likely to be considerably less severe than an unchecked fire, considering the effects of the preceding fire and the water application. The conclusion was, therefore, reached with reference to the columns in the investigation that the fire and water tests developed nothing that would modify conclusions from the results of the fire-endurance tests. This is significant, since in the series reported in this paper no fire and water tests

⁶ B. S. Tech. Paper, No. 184, pp. 48 and 53.

⁸ B. S. Tech. Paper, No. 184, pp. 158-159.

⁷ B. S. Tech. Paper, No. 184, p. 113.

were made, and the results from the other investigation indicate that for reinforced concrete columns of ordinary design conclusions can be safely based on results from fire tests alone.

Comparing the resistance periods deduced from the results of the other investigation, vertically and combined laterally and vertically reinforced columns made with trap-rock aggregate with 2 inches of concrete protection were given a period of five hours⁹ as against three and one-half and four hours for those in the present investigation with 1½-inch concrete protection. With limestone concrete columns the comparison stands eight hours against six hours on the same basis. The conclusions from the two investigations are believed consistent, considering the thinner protection of columns in the present investigation, and the intent to have the fire-resistance periods apply to columns near the minimum size used in buildings and of the range in reinforcement percentages allowed by current design standards.

No experimental investigations of the fire resistance of concrete columns, other than the one above referred to, have been made under conditions comparable with the present investigation, the few tests made being under no load or loads considerably below working load values and with fire exposures of different intensity.

4. INTENSITY AND DURATION OF FIRES IN BUILDINGS

To apply the fire-resistance periods derived from this investigation per the preceding section and Table 14 to the different building types and occupancies some knowledge is necessary of the intensity and duration of fires that destroy the building contents and combustible trim. Reinforced concrete columns will almost invariably be used in combination with concrete or other incombustible structural floors and floor framing. There may, however, be a considerable amount of combustible material in the top or finish floor, partitions, and interior trim. The combustible contents may vary in amount from a minimum with residential, institutional, and office occupancies, such as private residences, apartments, hotels, schools, hospitals, public and office buildings, to a range from minimum to near maximum with manufacturing and merchandizing.

The greatest amount of material and consequently the severest fires are to be expected in warehouses and storage buildings where fires apparently equivalent in intensity and duration to the four or

⁹ B. S. Tech. Paper, No. 184, p. 213.

five hour fire exposure in the tests have occurred. For residential, institutional, and office occupancy some experimental investigation recently conducted at the Bureau of Standards, as also observation of the effects of fires in buildings, indicate that fires in such buildings do not generally exceed a severity equivalent to the first hour of the fire-test exposure and severity greater than the one and one-half hour exposure would obtain only in portions used for storage or similar purposes. Merchandizing and manufacturing would accordingly present a range of severity equivalent to the one or two hour fire-test exposure at the lower limit and approximately to the four-hour period where material in the larger amounts are present.

This estimate of probable intensity and duration of fires, while admittedly tentative, is believed to have sufficient value to warrant its presentation as an aid in applying the results of this investigation to the common building types and occupancies and appears to be confirmed by fire experience to the extent that definite information has been obtainable from this source.

XVI. APPENDIX

TABLE 15.—Tension Tests of Spiral Reinforcement

Specimen No.	Diameter	Ultimate strength	Elongation	Reduction in area	Modulus of elasticity in million pounds per square inch
	Inch	Lbs./in. ²	Per cent	Per cent	
a.....	0.316	104,500	-----	44.8	30.4
b.....	.316	106,000	3.4	54.9	31.4
c.....	.312	103,000	3.4	44.7	29.1
Average.....	-----	104,500	3.4	48.1	30.3

TABLE 16.—Compressive Strength of Concrete and Mortar Cylinders

[Concrete cylinders, 6 by 12 inches, 1 : 2 : 4 Portland cement, sand, and coarse aggregates, by volume.
Mortar cylinders, 2 by 4 inches, 1 : 2 Portland cement and Pittsburgh sand, by weight. All cylinders
stored in damp closet until tested]

Column number	Concrete cylinders					Mortar cylinders	
	Aggregates	Number of cylinders	Age		Average compressive strength	Compressive strength (average of 5)	
			Months	Days		7 days	28 days
					Lbs./in. ²	Lbs./in. ²	Lbs./in. ²
1	Pittsburgh gravel and sand	3	6	15	3,608	1,593	3,202
2	do.	3	6	9	3,875	1,948	2,554
3	do.	7	7	9	3,488	1,665	2,684
4	do.	5	12	2	3,200	2,240	3,365
6	do.	5	6	10	2,316	2,203	3,618
7	do.	6	8	3	3,010	1,343	1,316
8	do.	6	7	19	3,400	1,586	2,610
9	do.	7	9	11	3,500		
10	do.	7	6	29	4,160		2,202
12	do.	5	7	10	2,980		2,772
14	do.	6	9	23	3,314	2,133	2,940
15	do.	7	7	10	2,966	1,915	2,760
25	do.	7	7	24	2,972	2,344	2,967
26	do.	6	8	4	2,960	1,752	3,186
27	do.	7	13	9	2,950	1,900	3,265
28	do.	7	7	1	3,135	1,811	2,810
33	do.	5	7	4	2,709	1,808	3,410
34	do.	5	9	2	3,965	2,025	3,683
35	do.	5	10	4	3,037	2,098	3,040
36	do.	5	7	6	2,910	1,564	2,397
41	do.	7	8	20	2,722	2,980	4,403
58	do.	3	4	11	1,850	2,500	2,920
59	do.	3	3	23	1,864	2,208	
60 ¹	do.	3	2	0	2,362	1,514	
61	do.	3	4	7	2,558	1,670	2,364
63	do.	3	9	17	1,816		2,678
64	do.	3	5	6	2,330		
65	do.	3	4	26	1,930		
66	do.	3	4	4	1,755	2,368	2,380
67	do.	3	4	22	2,062		
68	do.	2	4	0	2,066	2,291	2,444
69	do.	3	4	2	2,560		
70	do.	3	4	3	2,263		4,500
71	do.	3	4	0	2,186	2,350	2,740
72	do.	3	4	0	2,020	2,460	4,090
73	do.	3	4	0	2,540		
74	do.	3	4	0	2,075	3,270	4,450
77	do.	3	4	3	2,620	2,024	3,340
78	do.	3	4	0	2,130	2,920	4,250
80	do.	3	4	1	2,450	2,975	4,820
82	do.	3	4	3	2,324	2,550	3,988
83	do.	3	4	0	2,440	3,123	4,700
88	do.	3	4	1	2,114	2,993	4,370
Total		190					
Average			6	12	2,834	2,180	3,234
17	West Winfield (Pa.) limestone and Pittsburgh sand	5	7	1	4,240	2,071	2,870
18	do.	5	8	17	4,060	2,050	3,299
19	do.	6	10	23	2,862	2,061	3,760
20	do.	5	7	4	4,137	1,838	2,586
21	do.	7	7	7	3,849	2,083	3,159
22	do.	7	7	2	4,660	1,950	3,050

¹Cylinders from concrete of column 60 are 8 by 16 inches.

TABLE 16.—Compressive Strength of Concrete and Mortar Cylinders—Con.

Column number	Concrete cylinders				Mortar cylinders		
	Aggregates	Number of cylinders	Age		Average compressive strength	Compressive strength (average of 5)	
			Months	Days		7 days	28 days
23	West Winfield (Pa.) limestone and Pittsburgh sand	6	6	29	Lbs./in. ² 3,464	Lbs./in. ² 2,106	Lbs./in. ² 3,510
24	do	7	7	3	3,278	1,862	2,996
29	do	7	8	14	3,097	1,946	2,890
30	do	7	8	27	3,527	2,206	3,129
32	do	7	7	25	3,400	1,882	2,952
Total		69					
Average			7	28	3,664	2,005	3,109
42	Pure quartz gravel and Long Island sand	6	4	11	3,162	3,156	4,493
43	do	3	4	7	3,160	3,770	4,798
44	do	3	4	8	2,529	2,750	4,605
45	do	1	4	24	3,560		
Total		13					
Average			4	12	3,046	3,225	4,632
37	Long Island gravel and sand	7	8	7	2,400		4,275
38	do	7	8	22	2,569	2,628	3,417
39	do	5	12	11	2,560	1,904	2,625
46	do	1	4	2	3,204	2,053	3,367
47	do	3			1,760	2,590	3,643
Total		23					
Average					2,438	2,294	3,465
48	Blast-furnace slag and Pittsburgh sand	3	4	0	2,858	2,262	3,213
49	do	3			2,370	2,123	3,600
50	do	3	4	21	2,328	2,096	2,892
51	do	3	4	5	2,965	2,482	3,902
52	do	3	4	26	2,609	2,646	3,518
53	do	3	4	12	2,644	2,049	3,110
Total		18					
Average			4	13	2,629	2,276	3,372
54	New Jersey trap rock and Pittsburgh sand	3	4	7	2,540	2,030	3,078
55	do	3	4	16	3,108	1,830	2,960
56	do	3	4	5	2,200		
57	do	3	4	12	2,238	2,445	3,053
Total		12					
Average			4	10	2,522	2,102	3,030
85	Elgin (Ill.) gravel and sand	3	4	1	2,085		
86	do	3	4	1	2,434	3,365	
Total		6					
Average			4	1	2,260	3,365	
5						2,238	3,180
75						3,133	3,906
76							4,010
81						3,620	5,010
84						2,554	4,570
87						3,100	3,745
89						3,172	4,210
90						2,940	4,000
Grand average						2,306	3,463

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