Fire Tests of Steel Columns Protected With Siliceous Aggregate Concrete

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Building Materials and Structures Report 124

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NATIONAL BUREAU OF STANDARDS • E. U. Condon, *Director*

Fire Tests of Steel Columns Protected With Siliceous Aggregate Concrete

Nolan D. Mitchell

Building Materials and Structures Report 124

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Foreword

This report, one of a series issued by the National Bureau of Standards on building materials and structures, presents the results of fire tests of four steel building columns protected by concrete made with certain highly siliceous aggregates. The results of the column tests were further confirmed by tests on concrete walls made with the same aggregates. Such materials are available in widely distributed areas, and are common constituents of much of the commercially available concretes.

The fire-endurance limits of protected columns described in this report may serve as a guide for the selection of constructions to meet building code requirements, and as a measure of the extent of compliance of building practice with existing codes.

E. U. Condon, *Director.*

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Fire Tests of Steel Columns Protected With Siliceous Aggregate Concrete

Nolan D. Mitchell

Results of fire-endurance tests of four 6-in. steel H-columns protected with concrete made with highly siliceous aggregates are presented.[1] The concrete was of 2-in. thickness around the column shaft and filled the reentrant spaces. The aggregates investigated were river gravel and crushed quartz.

The columns were subjected to load throughout the tests. The loads on three columns of magnitude as computed by a standard formula for allowable load were constant. One column sustained a double load throughout the earlier part of the test.

The fire-endurance limits ranged from 2 hr 50 min for a column with crushed quartz aggregate concrete to 3 hr 34 min for one with gravel aggregate concrete. The results were consistent for columns protected with gravel aggregate concrete, and within reasonable limits for columns covered with quartz aggregate concrete.

The results of the column tests with respect to lack of spalling of the concrete were confirmed by tests on concrete wall slabs made with the same or like aggregates.

I. Introduction

Fire-endurance tests were conducted at the National Bureau of Standards on four 6-in. 20-lb H-columns having protective coverings of siliceous aggregate concrete. The aggregate for the concrete on two columns was Potomac River sand and gravel, on the third crushed milky quartz, and on the fourth clear crushed quartz. These aggregates are widespread both in distribution and use and are available in the vicinity of Washington, D. C.

The information developed by these tests supplements that derived from the tests of columns with concrete coverings included in the series of tests conducted jointly by the Associated Factory Mutual Fire Insurance Companies, the National Board of Fire Underwriters, and the National Bureau of Standards, at Underwriters' Laboratories, Chicago, in 1917–18.[2] Related through use of siliceous aggregates are the fire tests of concrete columns conducted at the former Pittsburgh testing station of the National Bureau of Standards.[3]

In the early tests, it was observed that column protections of concrete made with highly siliceous gravel aggregates cracked and spalled so as to expose the steel shaft or reinforcing of the column before its temperature had reached the critical range for failure under load. Further, siliceous aggregate concrete monolithic floors and walls showed varying and contradictory behavior in fire tests. To illustrate, a 6-in.-thick concrete floor slab made with Potomac River gravel concrete began spalling within 35 min after the start of the fire-endurance test. At 1 hr 45 min the fire had penetrated through a large hole formed in the spalled area. However, another floor specimen and three wall specimens made of concrete having aggregate from the same source showed no tendency to spall. The best surmise possible from the meager data was that the spalling could be due to the disruptive effect caused by superheating of water entrapped in the dense concrete.

The tests of columns at the National Bureau of Standards were for the purpose of again investigating the reaction of siliceous aggregate concretes to fire exposure, especially under the conditions of high stress peculiar to column encasements. To supplement the tests on the columns encased with siliceous aggregate concrete, results are given for four walls constructed of similar concretes. Three of these were made with Potomac River gravel and one with the crushed quartz that served as both the fine and coarse aggregates for the coverings of two of the four columns.

The columns, which were alike in size, were tested under an allowable load computed from a formula recommended by the American Institute of Steel Construction. However, as no tendency of the concrete to spall was evident in the first test, the second of the columns with gravel aggregate concrete protection was subjected to twice the load of the other columns until a specified temperature of the steel was attained to determine whether excessive strain would induce spalling of the encasement, after which the load was re-

[1] The term "siliceous" as used herein conforms to the usage in building codes in which it is construed to embrace the minerals composed wholly or largely of quartz, chert, flint, etc.

[2] Fire tests of building columns, Underwriters' Laboratories, 1920; also published as B. S. Tech. Pap. T184 (1921).

[3] Fire resistance of concrete columns by W. A. Hull and S. H. Ingberg, B. S. Tech. Pap. T272 (1925).

duced to that of the formula and maintained until failure had occurred.

The failure of silica gravel concrete protection observed early in the test at the Underwriters' Laboratories was not duplicated in the present tests. The fire-endurance limits for the columns of this series ranged from 2 hr 50 min to 3 hr 34 min.

It should be noted that, although both groups of tests used concrete made with siliceous aggregates, there was dissimilarity in composition of the aggregates of the two groups. The aggregates of the concrete that failed earliest in the tests at the Underwriters' Laboratories contained 98 percent of chert, whereas the aggregate for the concrete used for the present tests consisted of either a mixture containing principally quartz, sandstone, and quartzite, with only a minor quantity of chert or a relatively pure crushed quartz. Also, despite the general assumption of poor performance of siliceous aggregate concretes, columns protected with this material have shown a reasonable resistance to fire. This is indicated by tests made at the Underwriters' Laboratories where an 8 in. column protected with 2 in. of sandstone concrete showed a fire-endurance limit exceeding 4 hr, even though considerable cracking and spalling of the concrete had occurred early in the test.

II. Materials

1. Steel Columns

The column shafts were fabricated from 6-in. 20-lb stanchion sections 5.97 in.^{2} in area. The heads of the columns were restrained for 32 to 33 in. by ½-in. plates of two types, leaving an effective column length of 124 in. End fittings were so applied as to allow the milled ends of the column shafts to rest directly on the 1⅞-in.-thick planed steel bearing plates. The column fitting assemblies were made with hot rivets. The least radius of gyration of the columns was 1.5 in. and the l/r ratio was 82.67. Figure 1 shows a column in place after a fire test. The details of the column shafts are shown in figure 2.

FIGURE 1. *A test column in furnace after fire exposure.*

2. Concrete

The concrete for encasing the first two columns of the tests was made of 1 part of portland cement, 2½ parts of Potomac River concrete sand, and 3½ parts of Potomac River gravel. Equal parts of two sizes of screened gravel were mixed to produce the coarse aggregate. The densities of the sand and screened gravel were determined, and the batches were proportioned by weight of materials. A typical batch consisted of 94 lb (1 bag) of cement, 300 lb of damp sand, 197 lb of fine gravel, 181 lb of coarse gravel and 6½ gal water.

The sieve and petrographic analyses of the aggregates used in the concretes are shown in table 1.

TABLE 1. *Sieve and petrographic analyses of concrete aggregates*

Sieve designation	Sieve analysis of concrete aggregates—percentage retained					
	Potomac River gravel	Potomac River sand	Clear crushed quartz	Milky crushed quartz	Clear crushed quartz sand	Milky crushed quartz sand
¾ in.	0.0	0.0	0.0	0.0	0.0	0.0
⅜ in.	[a] 50.0	.0	1.7	1.2	.0	.0
No. 4	50.0	4.9	40.3	42.6	.0	.0
No. 8	0.0	19.5	53.7	53.5	.0	.1
No. 16	.0	13.7	3.4	2.1	.2	.1
No. 30	.0	13.2	0.2	0.1	5.7	2.2
No. 50	.0	22.5	.1	.1	42.1	61.7
No. 100	.0	18.8	.2	.1	38.5	29.5
Pan	.0	7.4	.4	.3	13.5	6.4
Minerals	**Petrographic analyses of concrete aggregates: Mineral content—percent**					
Vein quartz	21	90	100	100	100	100
Quartzite	38					
Sandstone	23					
Chert	12					
Mica		4				
Other [b]	6	6				

[a] Potomac River gravel screened to size.
[b] One or more of the following: chlorite, magnetite, schist, gneiss.

In the tests, the third and fourth columns were covered with concrete made with fine and coarse aggregates of relatively high purity; that for one was of milky quartz, the other of a clear variety. Photomicrographs of these materials, figure 3,

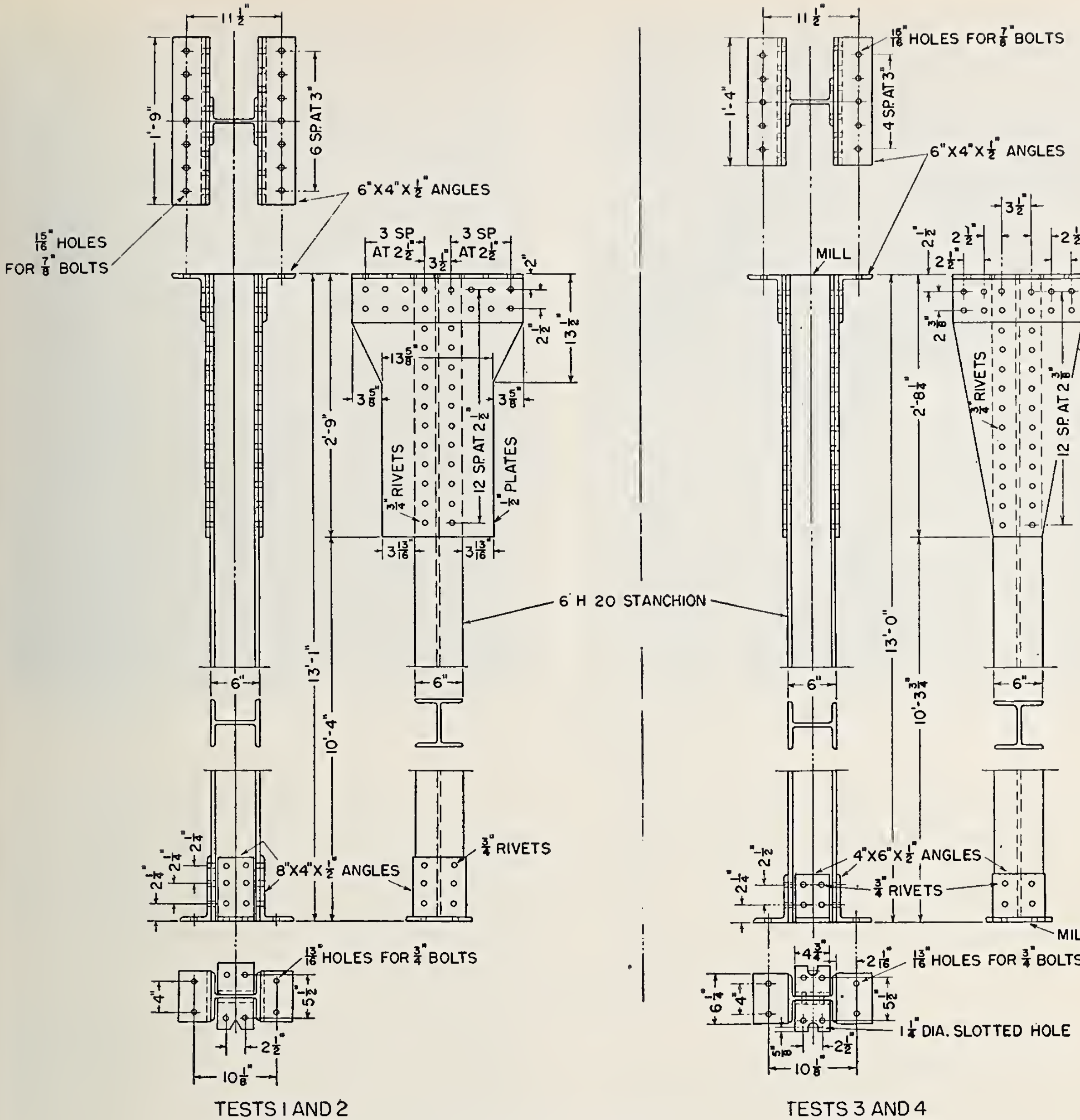

FIGURE 2. *Details of columns.*

show small inclusions. Because of the unusual grading of the coarse quartz aggregate, a workable mix was found to have the proportions approximately 1 part of cement, 3 parts of sand, and 2 parts of coarse aggregate. The batches were proportioned by weight and consisted of 94 lb (1 bag) of cement, 293 lb of quartz sand, and 195 lb of crushed quartz.

Each batch was mixed for not less than 1½ min dry and 2 min wet. Three test cylinders were cast from each of four batches of Potomac River aggregate concrete and three each from the single full batches of the milky and of the clear-quartz aggregate concretes. The water was controlled to give slumps of concrete in the range of 6 to 8 in.

The average compressive strength of the cylinders of Potomac River gravel aggregate concrete was 2,580 lb/in^2. The average batch strengths ranged from 2,240 to 2,800 lb/in^2. The initial tangent modulus of elasticity of six cylinders was 2.97×10^6 lb/in^2. The modulus determined from stress-strain relations at a working load of 1,600 lb/in.^{2} was 2.03×10^6 lb/in^2.

For the concrete made with milky quartz aggregate, the average compressive strength of three cylinders was 1,930 lb/in^2. The initial

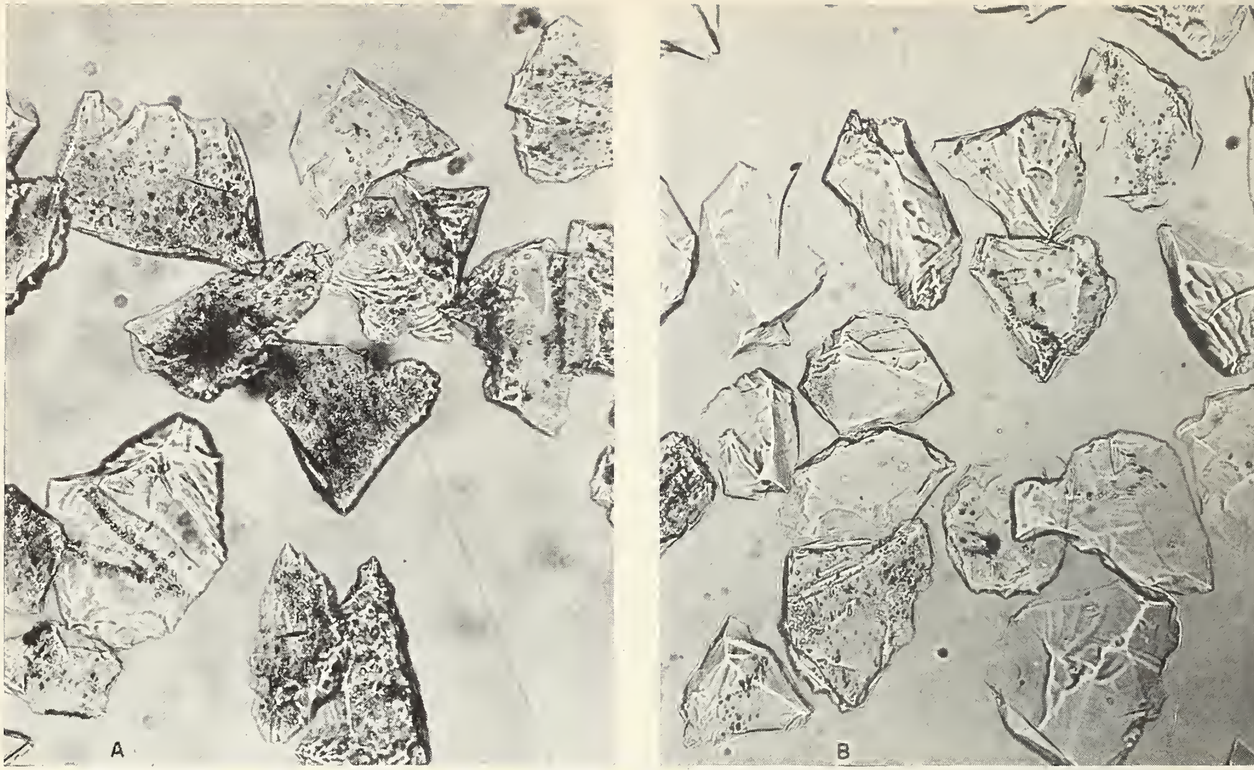

FIGURE 3. *Photomicrographs of crushed quartz aggregates showing inclusions or voids (X96):* A, *milky;* B, *clear.*

tangent elastic modulus as determined on one cylinder was 2.8×10^6 lb/in^2. The three cylinders made with clear quartz aggregate concrete had an average compressive strength of 2,600 lb/in^2. The modulus of elasticity for one of these cylinders determined from the initial tangent was 2.6×10^6 lb/in^2.

In all of the tests, a No. 8 SWG wire (0.16 in. in diameter) wound spirally around the column on an 8-in. pitch provided anchorage for the concrete covering. The wire spiral had 1-in. clearance at the midwidths of the column flanges, leaving a distance of 1 in. from the wire to the outside surface of the concrete. Thus the wire was covered with 1 in. of concrete at the midwidth of each of the four sides of the column.

III. Construction of Columns

1. Placement of Concrete

Plywood forms were spaced 2 in. on all sides from the vertically placed column shafts. Concrete poured into the tops of the forms was compacted around the columns by vibrating the sides of the forms with an air hammer. The few small voids, visible after the forms were removed, were filled with a cement and sand mortar.

A 4- by 8-ft. by 4-in.-thick wall slab was poured from the same batches of the clear and of the milky quartz aggregate concretes that were used for the column coverings. The slab was divided into quarters with the sections of like aggregate concrete diagonally opposite each other.

2. Workmanship

The steel columns were of good commercial quality of fabrication. The concrete was of ordinary good workmanship with a mixing time exceeding that of the prescribed minimum, and was well placed with the exception that the form around the enlarged portion of the top of one column was through inadvertence laterally displaced about 1 in. As this imperfection occurred in the upper restrained portion of the column, well above the section under test, it was thought incapable of adversely affecting the results.

3. Seasoning of Concrete

The forms were stripped from the columns encased with Potomac River gravel concrete on the fifth day after pouring. The columns were kept moist for 8 days. Beginning the ninth day after removal of forms, the weights of the columns were checked until such time as drying was essentially complete. In 30 days, concrete that weighed approximately 2,900 lb had lost 37 lb, after which its weight remained constant.

The column protections of crushed quartz aggregate concrete were allowed to remain in the forms 15 days, after which the concrete was kept moist 5 days. The concrete was further seasoned under atmospheric conditions for 2½ months prior to test.

IV. Equipment and Method of Testing

1. Equipment

The tests were made in gas-fired furnaces equipped with hydraulic jacks for applying load. The furnace, loading equipment, and the column under test are shown in figure 4. The furnace, while not originally designed for columns, was modified by an increase in height to accommodate a column having an effective length of 124 in.

The jack piston was raised by an electrically driven oil pump equipped for automatic control of pressures. The movable floor of the furnace rested on a spherical bearing block raised and lowered by the hydraulic jack.

Temperatures at 12 locations in the furnace were measured with chromel-alumel thermocouples protected by iron tubes. The temperatures at 16 or more points on each column were also measured with similar thermocouples made of No. 18 AWG wires. The thermocouple junctions were formed by inserting carefully cleaned ends of the respective wires into 1.1-mm diameter paired holes spaced at ¼ in. drilled into the column shaft. Steel was swaged around the holes to secure metal-to-metal contact with the wires. The thermocouples were disposed at each of four levels of the column shafts as indicated by the positions B, N, M, and T in figure 4.

2. Method of Testing

(a) Bearing of Columns

Steel bearing plates were bolted at either end of a test column. The plate at the bottom was 20 in. sq and 1⅞ in. thick. The top plate, 25 by 27 by 1⅞ in. was fixed to the column with fourteen ⅞-in. bolts 2½ in. long, and in turn was bolted to the overhead bearing of the loading frame of the furnace in such a position as to center the bottom plate over the loading jack. The furnace floor was then raised to within ¾ in. of the bottom plate and the space between filled with portland cement grout. As the floor rested on a well-lubricated ball-and-socket joint coincident with the vertical center line of the column shaft, the column was considered to have a spherical end bearing at its lower extremity.

(b) Restraint of Columns

The plates attached to the head of a column were designed to give effective restraint against bending of the upper 33 in., thus offering substantially full continuity from the top of the fire-exposed test portion of the column shaft to the overhead bearing.

(c) Loads on Columns

The load imposed during the test on three of the columns was computed from a formula for allowable load recommended by the American Institute of Steel Construction

$$P=\left(17{,}000-0.485\,\frac{l^2}{r^2}\right)A,$$

in which $P=81{,}700$ lb, total load on a column, equivalent to a stress of 13,700 lb/in.^{2} on the cross-sectional area A of the column (5.97 in.^{2}); $l=124$ in., the effective length of the column; $r=1.50$ in., the least radius of gyration of the steel column.

The load was applied before starting the test fire and was maintained until rapid yielding of the column occurred, the load being removed when the yield of a column from its maximum expansion amounted to approximately 0.6 in., or three-fourths of the amount of its expansion.

The second of the columns protected with Potomac River gravel aggregate concrete was loaded to 163,000 lb before the test, and this load was maintained until the average of the temperatures at 16 points in the steel reached 445° C (833° F), the maximum at any of the 16 points being 490° C (914° F). These temperatures were attained in 1 hr 51 min after the start of the test, at which time the load was reduced to that of the other tests.

(d) Measurement of Deformations

Movement of the piston of the hydraulic jack as observed on a dial indicator was taken as a measure of the longitudinal deformation of a column. Measurements made during previous tests indicated that the thermal expansion of the vertical framework was closely compensated by the expansion of the unexposed section of the column and the thermal deflections of the overhead beams supporting the upper bearing plate. No measurements of the lateral deflections of a column were made during or after a test.

(e) Test Specification

The tests were conducted in accordance with the American Society for Testing Materials Standard Methods of Fire Tests of Building Construction and Materials, E119–41 (ASA No. 2.1–1942) as applicable to loaded columns. The loading schedule for one column, as previously described, deviated from that of the specification.

The limit of fire endurance was selected as the time from the start required to attain a yield of about 0.6 in. from the point of maximum expansion of a column.

V. Results of Tests

1. Columns 1 and 2—Potomac River Gravel Aggregate Concrete Protections

The results of fire tests of columns protected with concrete made with Potomac River gravel aggregate are shown in figures 5 and 6.

Figure 5 shows the temperatures within the furnace and the standard furnace reference curve. Also shown are the maximum observed temperatures at any thermocouple, the temperatures at the level having the highest average most consistently, and the minimum level temperatures in a column. The average of temperatures for the several levels are arithmetical. They were not weighted in proportion to the areas involved as were those reported in previous tests.[4] It was considered that the greater temperature effects on the column strength at the edges of the flanges, as compared to the effects at the midpoint of the flange or web, compensated for the smaller cross-sectional area contributory to each thermocouple near the edges.

The failure of both columns involved deformation throughout the fire-exposed lengths. The lateral deformation of column 1 was somewhat greater than that of column 2 and was centered somewhat lower in the shaft. Although the lateral deflections were unequal, the total shortening of both columns, as determined by measurements before and after the tests, was the same, 0.4 in.

The expansion of the columns with increases in the average temperatures of the steel shafts are shown in figure 6. Column 2 was subjected to double the load applied to column 1 until the average temperature in the shaft reached 445° C (883° F), after which the load was reduced to that of column 1.

Yielding of the steel under constant load with increasing temperature began in column 1 after the average temperature of the steel shaft had exceeded 570° C (1,058° F) and in column 2 after it had exceeded 610° C (1,130° F). End-point temperatures for column 1 were 730° C (1,346° F) as the average of all thermocouples and 775° C (1,427° F) maximum at one location; for column 2, 725° C (1,337° F) was the average end-point temperature and 760° C (1,400° F), the maximum at one location. The fire-endurance limit for column 1 was 3 hr 34 min and for column 2, 3 hr 32 min.

The condition of the gravel aggregate concrete column protections after the fire test are shown in figures 1 and 7. Figure 8 shows the two columns after removal of the concrete encasement.

The Potomac River gravel concrete of three monolithic walls did not spall or develop serious cracks throughout the fire- and load-test periods. Two reinforced concrete walls 4 and 6 in. thick were exposed for 1 hr 27 min and 4 hr, respectively. Figure 9 shows the fire-exposed face of an 8-in. unreinforced wall after 5½ hr test. These walls suffered only minor cracking and in no case was there evidence of spalling.

[4] Fire tests of building columns, Underwriters' Laboratories 1920; also published as B. S. Tech. Pap. T184 (1921).

2. Columns 3 and 4—Milky and Clear Quartz Aggregate Concrete Protections

Figures 10 and 11 show the results of fire tests on steel columns protected with crushed quartz aggregate concrete. Temperatures within the furnace and the standard reference curve are shown in figure 10, as well as the observed temperature at any thermocouple in a column, the temperature at the level having the highest average most consistently, and the minimum average temperature at one level. As was true for the first two columns, the averages are arithmetical and not weighted.

Both columns suffered lateral deformations in their fire-exposed portions. The concrete with milky quartz aggregate of column 3 showed only minor cracking at the end of the test, as is seen in figure 12. Failure to cease application of the load at the end of the test when the contraction had reached the predetermined value of ⅝ in. caused severe bending of the shaft of column 4. The clear quartz aggregate concrete showed little cracking and no evidence of spalling prior to the excessive deformation.

The expansion of the columns with increase in average temperature of the shafts is shown in figure 11. Yielding under constant load and increasing temperature began in column 3 at an average temperature of the steel of 525° C (977° F) and in column 4 at 535° C (995° F). End-point temperatures for column 3 at the fire-endurance limit of 3 hr 10 min were 625° C (1,157° F) as the average of all thermocouples and 730° C (1,346° F) maximum at any one thermocouple. For column 4, the average end-point temperature was 620° C (1,148° F) and the single point maximum was 755° C (1,391° F). The fire-endurance limit was 2 hr 50 min. A correction of 4 min may be added to the fire-endurance time of column 3 because of the excess of the furnace exposure over the standard.

The quartz aggregate concrete of a 4- by 8-ft wall slab 4 in. thick showed only a fine crack in the line of a pouring joint after a fire exposure of 1½ hr. The slab was poured in quarters from the same milky and clear quartz concrete batches used for columns 3 and 4, the sections with like aggregate being diagonally opposite. Figure 13 shows the fire-exposed face of the wall after removal from the furnace.

VI. Summary and Discussion

The steel columns of these tests were of a type commonly used as structural members. The concrete protections were made with siliceous aggregates of widespread occurrence. The concrete used on columns 1 and 2, made with a gravel

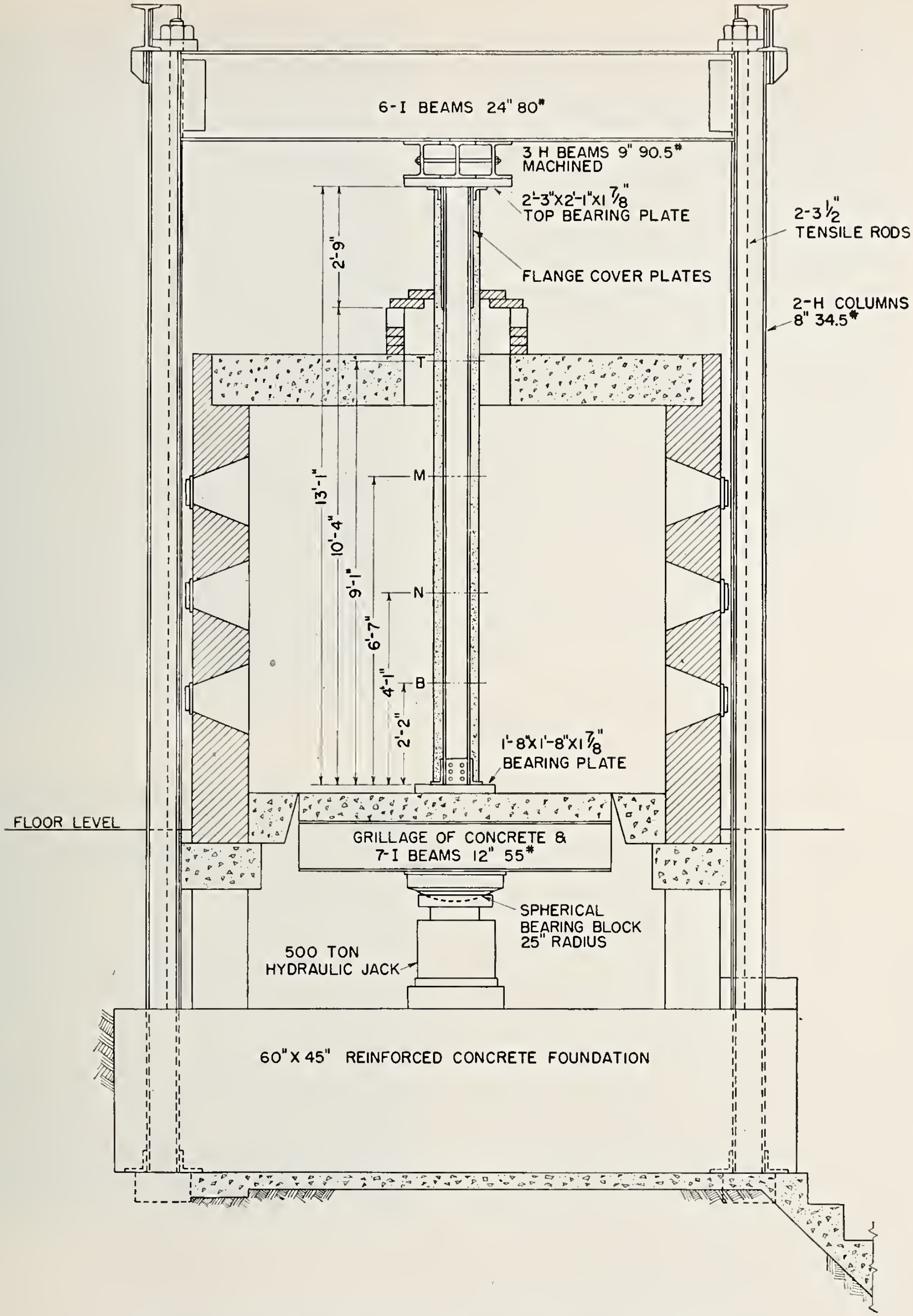

FIGURE 4. *Furnace and loading equipment with typical column in place.*

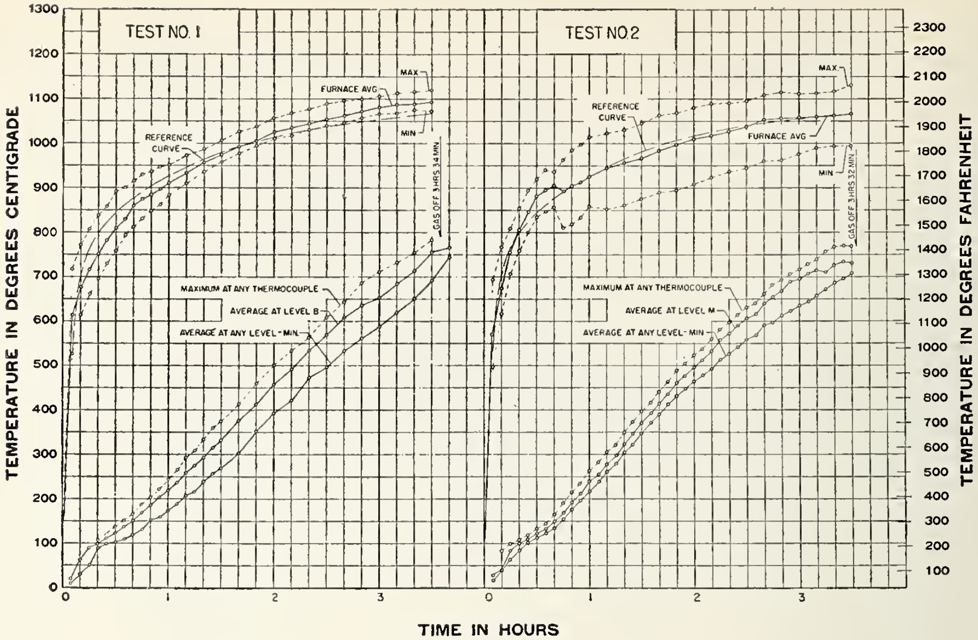

Figure 5. *Furnace and column temperatures for columns with Potomac River gravel concrete—Tests 1 and 2.*

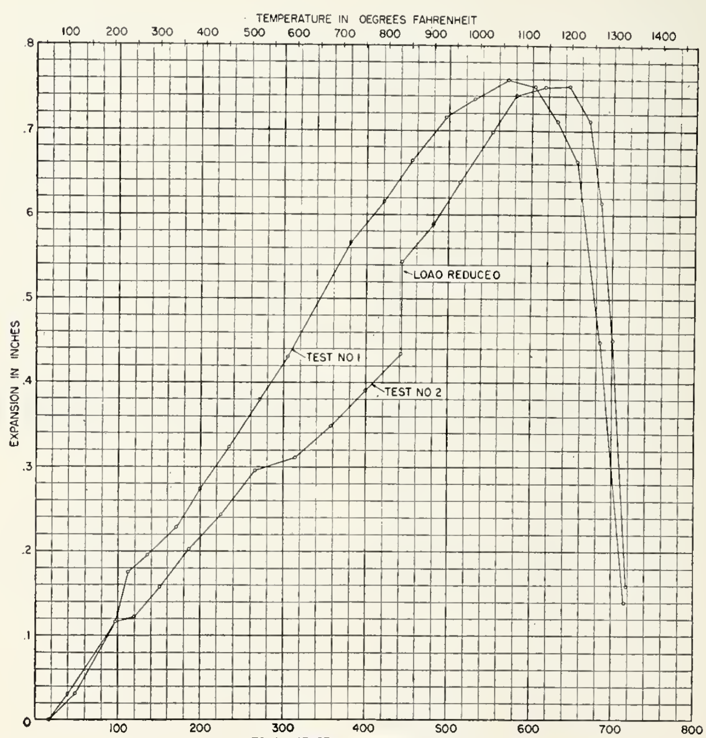

Figure 6. *Expansion curves for columns with Potomac River gravel concrete—Tests 1 and 2.*

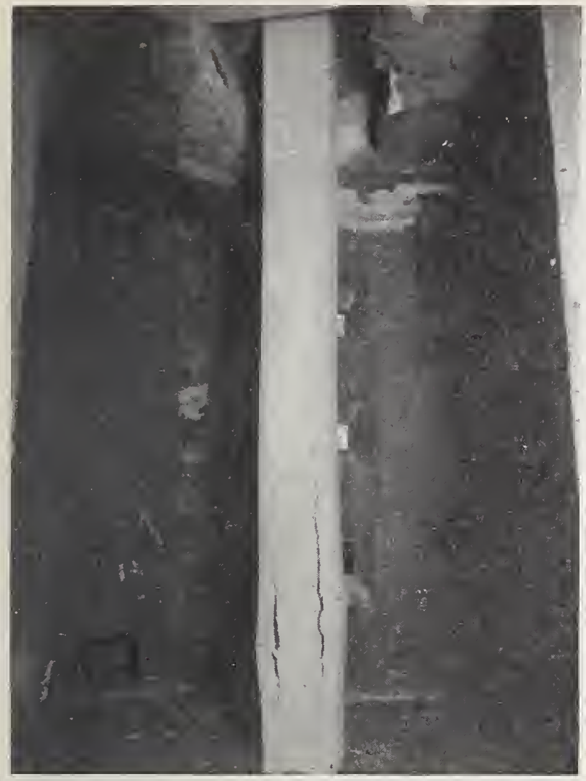

FIGURE 7. *Condition of gravel aggregate concrete column protection after 3½-hr fire exposure.*

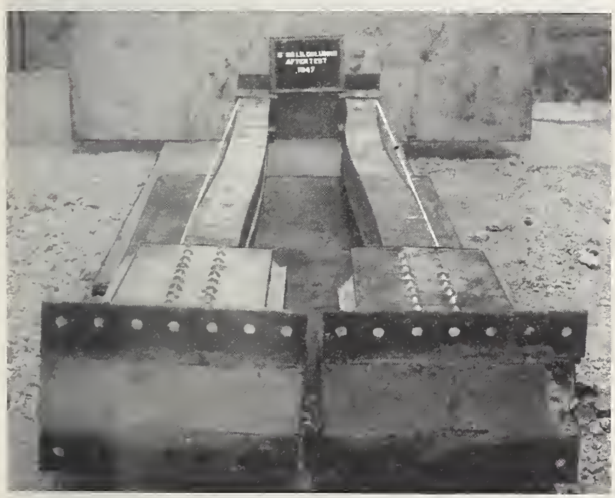

FIGURE 8. *Condition of columns after tests 1 and 2—Concrete removed.*

aggregate, was of conventional mix. The concrete with crushed quartz aggregate, however, had a disproportionate amount of sand, necessitated by the difficulty of working and the unusual fineness, sharpness, and gradation of the crushed sand and stone.

The columns were subjected to the loads computed by a formula for allowable loads recommended by the American Institute of Steel Construction. One column with Potomac River gravel aggregate concrete was subjected to a load twice that of the other columns until an average column temperature of 445° C (833° F) was attained, after which the load was reduced to that under which the other columns were tested. The delay in yield of this column can possibly be attributed to set caused by the greater load imposed on the column during the early part of the test. However, the double load did not reach the compressive yield strength of structural steel at the attained temperature of 445° C.[5]

The fire-endurance limits of columns with Potomac River aggregate concrete was somewhat greater than that of columns made with crushed quartz aggregate. The comparative times were 3 hr 34 min and 3 hr 32 min with the gravel aggregate concrete, and 3 hr 10 min and 2 hr 50 min with the quartz. The maximum measured expansions of the columns ranged from 0.59 to 0.76 in. The end-point temperatures as averages of the thermocouple readings at four levels for columns 1 through 4, respectively, were 730° C (1,346° F), 725° C (1,337° F), 625° C (1,157° F), and 620° C (1,148° F). The corresponding single-point maximums were 775° C (1,427° F), 760° C (1,400° F), 730° C (1,346° F), and 755° C (1,391° F).

The fire resistance of structural-steel columns with solid concrete protections and all reentrant spaces filled with concrete, can be estimated from the formula[6]

$$R=c\left(D-0.4\,\frac{d^2}{D}\right)^{1.7},$$

where

R= the fire resistance of the column
D= the dimension of the outside column section
d= the dimension of the inside section or core
c= a constant depending on the composition of the concrete.

Substituting the fire-endurance limits which are the results of the present tests, and the column dimensions, coefficient c becomes 5.5 for columns with Potomac River gravel aggregate concrete, 4.9 for milky quartz aggregate, and 4.4 for clear quartz aggregate.

The fire resistance of columns with 8-, 10-, and 12-in. steel shafts protected by 2-in. coverings of concrete, as determined from the formula, are shown in table 2.

The results obtained from the tests reported herein indicate that the conclusions reached in the fire tests of siliceous aggregate concrete for column protection as reported in National Bureau of Standards Technologic Papers 184 (1920) and 272 (1925) need to be reexamined. In the present tests there was no spalling of concrete such as had been reported in the previous tests and the cracking was not sufficient to expose the shaft before the critical-temperature range of the steel was attained.

[5] P. D. Sale, Compression tests of structural steel at elevated temperature, J. Research NBS **13**, 713 (1934) RP741.
[6] Fire-resistance classifications of building constructions, NBS Building Materials and Structures Report BMS92, p. 70 (1942).

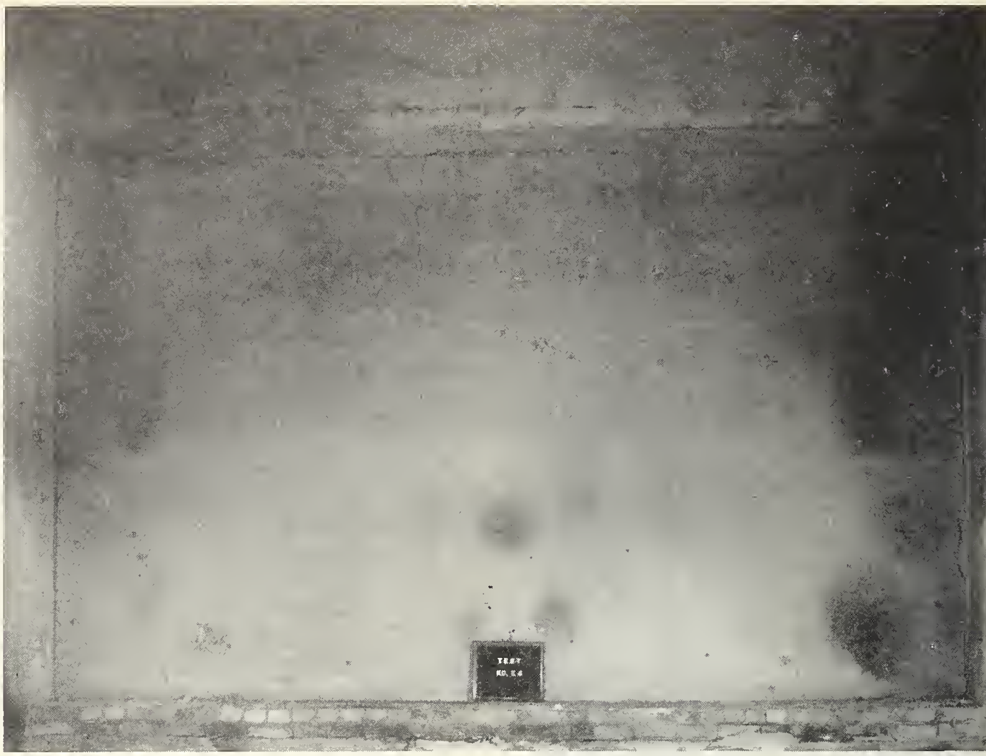

Figure 9. *Fire-exposed face of an 8-in. unreinforced wall of Potomac River gravel concrete after 5½-hr test.*

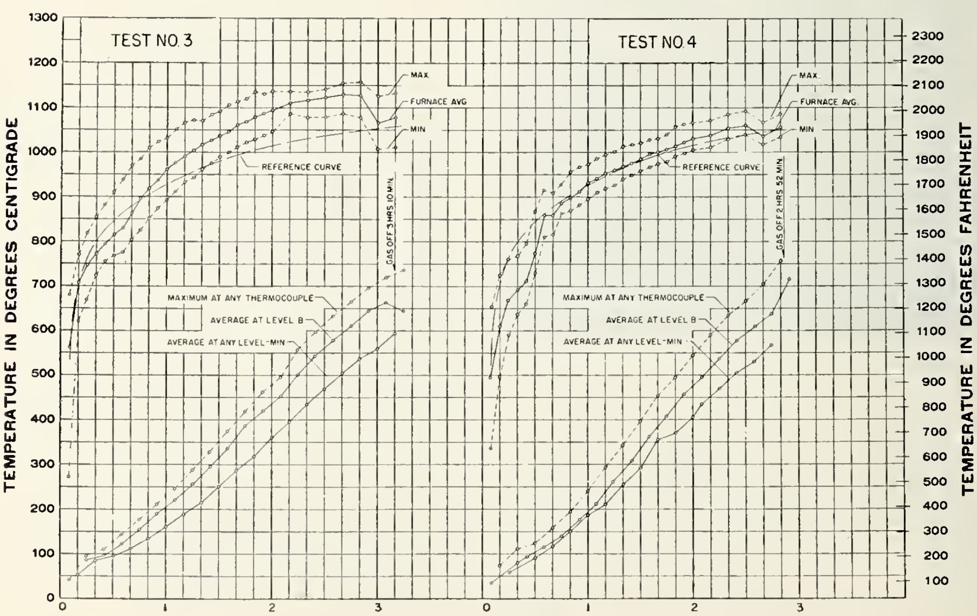

Figure 10. *Furnace and column temperatures for columns with crushed quartz concrete—Tests 3 and 4.*

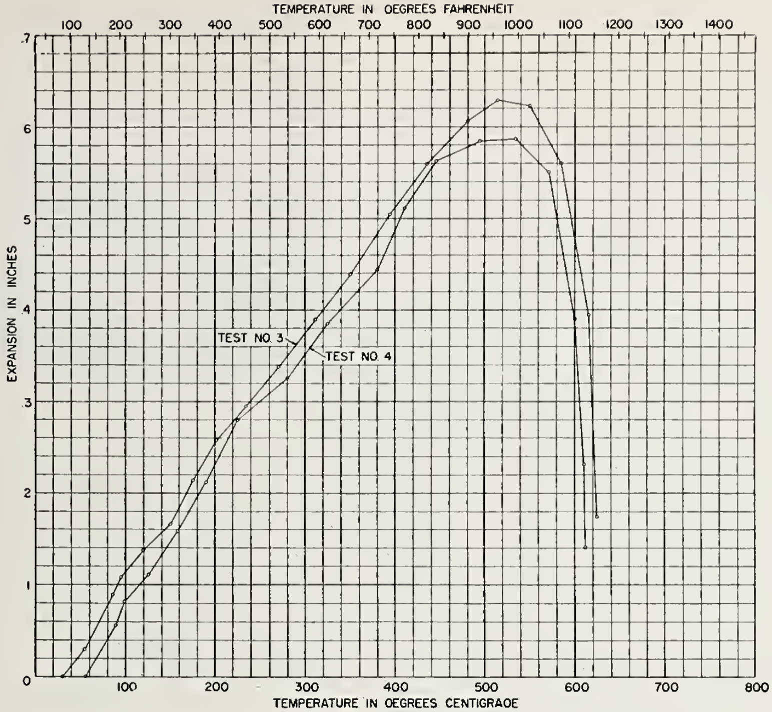

FIGURE 11. *Expansion curves for columns with crushed quartz aggregate concrete—Tests 3 and 4.*

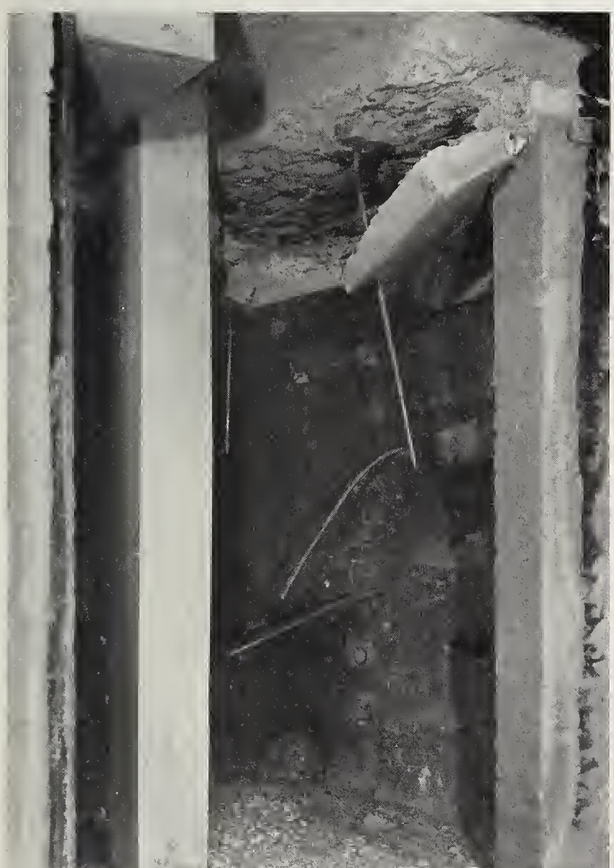

FIGURE 12. *Column protected with milky quartz aggregate concrete after 3-hr 10-min fire exposure—Test 3.*

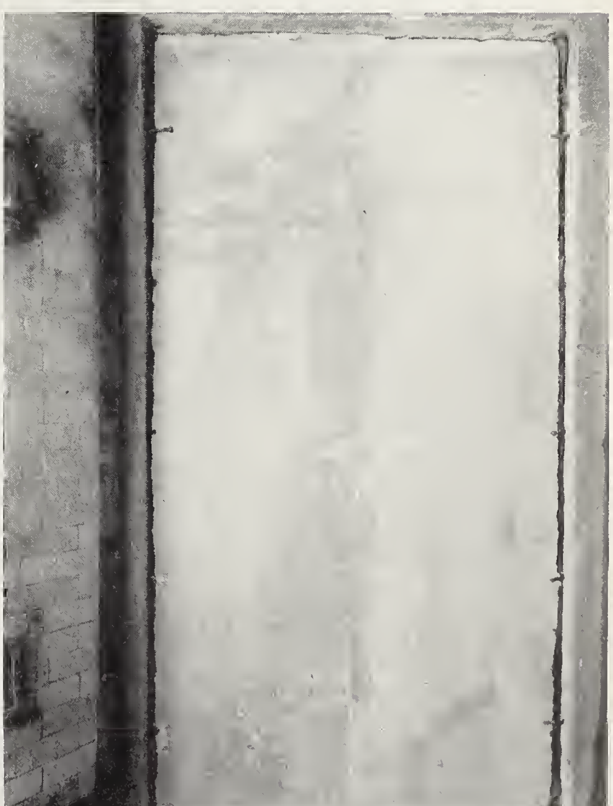

FIGURE 13. *Fire-exposed face of a crushed quartz concrete wall slab after 1½-hr test.*

Table 2. *Derived fire-resistance ratings of steel shaft H-columns with 2 inches of concrete protection*

Concrete aggregate	Size of column shaft	Fire-resistance rating
	in.	*hr*
Potomac River gravel	8	4½
	10	5½
	12	6½
Milky quartz	8	4
	10	5
	12	6
Clear quartz	8	3½
	10	4½
	12	5¼

The resistance of a concrete to high temperatures is probably influenced by its density. The spalling caused by the explosion resulting from superheated water in a dense concrete was previously mentioned in connection with the failure of a floor slab made with siliceous aggregate concrete. Further evidence of this effect can be seen in figure 12, which shows failure of the concrete top of the furnace after the first fire-endurance test to which the concrete was subjected. The failure occurred with explosive force 34 min after a 3-hr 10-min fire exposure, at which time the furnace still retained considerable heat. Examination of the debris showed the concrete, made with carefully graded firebrick aggregate, to be extremely compact. The structure of the spalled material can be seen in the photograph of the sample in figure 14.

The aggregates used in both series of tests, while siliceous in character, differed in mineralogical composition. Those composed largely of chert

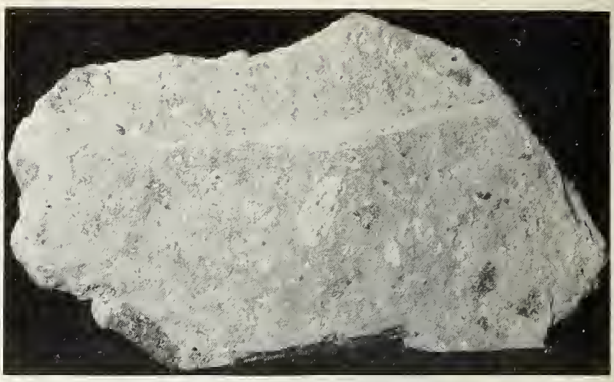

Figure 14. *Sample of firebrick aggregate concrete spalled from top of furnace.*

gave the poorest results in the tests at Underwriters' Laboratories. It is possible that an impurity or vaporizing water in the chert caused a disruptive force upon the application of heat. The characteristically rapid volume change of the siliceous minerals at critically high temperatures had no apparent effect upon the concrete used in the present tests.

The results of the tests indicate that concrete made with siliceous aggregates, as herein described, provides an acceptable material for the protection of structural steel against fire. The consistency of the results allowed definite conclusions as to the reliability of the protections for the demonstrated fire-endurance limits.

Washington, September 12, 1950.

U. S. GOVERNMENT PRINTING OFFICE: 1951

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