

Fire and Concrete Structures

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Abstract

After the 9-11 attack on the World Trade Center, interest in the design of structures for fire greatly increased. Some engineers have promoted the use of advanced analytical models to determine fire growth within a compartment and have used finite element models of structural components to determine temperatures within a component by heat transfer analysis. Following the calculation of temperatures, the mechanical properties at various times during the period of the fire must be determined. This paper provides structural engineers with a summary of the complex behavior of structures in fire and the simplified techniques which have been used successfully for many years to design concrete structures to resist the effects of severe fires.

Introduction

One of the advantages of concrete over other building materials is its inherent fire-resistive properties; however, concrete structures must still be designed for fire effects. Structural components still must be able to withstand dead and live loads without collapse even though the rise in temperature causes a decrease in the strength and modulus of elasticity for concrete and steel reinforcement. In addition, fully developed fires cause expansion of structural components and the resulting stresses and strains must be resisted.

In the design of structures, building code requirements for fire resistance are sometimes overlooked and this may lead to costly mistakes. It is not uncommon, to find that a concrete slab floor system may require a smaller thickness to satisfy ACI 318 strength requirements than the thickness required by a building code for a 2-hour fire resistance. For sound and safe design, fire considerations must, be part of the preliminary design stage.

Determining the fire rating for a structure member, can vary in complicity from extracting the relevant rating using a simple table to a fairly complex and elaborate analysis. In the United States, structural design for fire safety is based on prescriptive approach. Attempts are being made to develop performance based design approach for structural design for fire. State and municipal building codes throughout the country regulate the fire resistance of the various elements and assemblies comprising a building structure. The 2006 International Building Code (IBC) (1) contains prescriptive requirements for building elements in Section 720. This section is based on ACI 216.1 “Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies and contains tables describing various assemblies of building materials and finishes that meet specific fire ratings.

Effect of Fire on Building Materials

A relatively new method for determining fire exposure used by fire protection engineers is to first calculate the fire load density in a compartment. Then, based on the ventilation conditions and an assumed source of combustion determine the compartment temperature at various times. Another factor considered in the analysis is the effect of active fire protection systems e.g. sprinklers or fire brigades on the growth of the fire. The size and timing of the fire growth determined by fire analysis is sensitive to changes in the fuel load over time and changing ventilation conditions during the fire. This method of fire analysis requires special software and extensive training and is used only in very large or unusual buildings.

Once the temperature time relationship is determined using a standard curve or from the method described above, the effect of the rise in temperature on the structure can be determined. The rise in temperature causes the free water in concrete to change from a liquid state to a gaseous state. This change in state causes changes in the rate with which heat is transmitted from the surface into the interior of the concrete component.

The rise in temperature causes a decrease in the strength and modulus of elasticity for both concrete and steel reinforcement. However, the rate at which the strength and modulus decrease depends on the rate of increase in the temperature of the fire and the insulating properties of concrete. Note that concrete does not burn.

Concrete

The change in concrete properties due to high temperature depends on the type of coarse aggregate used. Aggregate used in concrete can be classified into three types: carbonate, siliceous and lightweight. Carbonate aggregates include limestone and dolomite. Siliceous aggregate include materials consisting of silica and include granite and sandstone. Lightweight aggregates are usually manufactured by heating shale, slate, or clay,.

Figure 1 shows the effect of high temperature on the compressive strength of concrete. The specimens represented in the figure were stressed to 40% of their compressive strength during the heating period. After the designated test temperature was reached, the load was increased gradually until the specimen failed. The figure shows that the strength of concrete containing siliceous aggregate begins to drop off at about 800 °F and is reduced to about 55% at 1200^{o}F. Concrete containing lightweight aggregates and carbonate aggregates retain most of their compressive strength up to about 1200 ^{o}F. Lightweight concrete has insulating properties, and transmits heat at a slower rate than normal weight concrete with the same thickness, and therefore generally provides increased fire resistance.

Figure 2 shows the effect of high temperature on the modulus of elasticity of concrete. The figure shows that the modulus of elasticity for concretes manufactured of all three types of aggregates is reduced with the increase in temperature. Also, at high temperatures, creep and relaxation for concrete increase significantly.

Steel

Reinforcing steel is much more sensitive to high temperatures than concrete. Figure 3 shows the effect of high temperature on the yield strength of steel. Figure 4 shows the effect on the modulus of elasticity. As indicated in the figures, hot-rolled steels (reinforcing bars) retain much of their yield strength up to about 800 °F, while cold-drawn steels (prestressing strands) begin to lose strength at about 500 °F. Fire resistance ratings therefore vary between prestressed and nonprestressed elements, as well as for different types of concrete.

Fire Resistance Rating

Fire resistance can be defined as the ability of structural elements to withstand fire or to give protection from it (2). This includes the ability to confine a fire or to continue to perform a given structural function, or both. Fire Resistance Rating (or fire rating), is defined as the duration of time that an assembly (roof, floor, beam, wall, or column) can endure a "standard fire" as defined in ASTM E 119 (3).

Fire Endurance of Structures

Figure 5 shows the effect of fire on the resistance of a simply supported reinforced concrete slab. If the bottom side of the slab is subjected to fire, the strength of the concrete and the reinforcing steel will decrease as the temperature increase. However, it can take up to three hours for the heat to penetrate through the concrete cover to the steel reinforcement. As the strength of the steel reinforcement decreases, the moment capacity of the slab decreases. When the moment capacity of the slab is reduced to the magnitude of the moment caused by the applied load, flexural collapse will occur. It is important to point out that duration of fire until the reinforcing steel reaches the critical strength depends on the protection to the reinforcement provided by the concrete cover.

ASTM E119 Standard Fire Test

The fire-resistive properties of building components and structural assemblies are determined by fire test methods. The most widely used and nationally accepted test procedure is that developed by the American Society of Testing and Materials (ASTM). It is designated as ASTM E 119, Standard Methods of Fire Tests of Building Construction and Materials. A standard fire test is conducted by placing a full size assembly in a test furnace. Floor and roof specimens are exposed to a controlled fire from beneath, beams are exposed from the bottom and sides, walls from one side, and columns are exposed to fire from all sides. The temperature is raised in the furnace over a given period of time in accordance with ASTM E 119 standard time-temperature curve shown in Figure 6. This specified time-temperature relationship provides for a furnace temperature of 1000^{o}F at five minutes from the beginning of the test, 1300^{o}F at 10 minutes, 1700^{o}F at one hour, 1850^{o}F at two hours, and 2000^{o}F at four hours. The end of the test is reached and the fire endurance of the specimen is established when any one of the following conditions first occurs:

1. For walls, floors, and roof assemblies, the temperature of the unexposed surface rises an average of 150^{o}F above its initial temperature of 325^{o}F at any location. In addition, walls

achieving a rating classification of one hour or greater must withstand the impact, erosion and cooling affects of a hose steam test.
2. Cotton waste placed on the unexposed side of a wall, floor, or roof system is ignited through cracks or fissures which develop in the specimen during the test.
3. The test assembly fails to sustain the applied service load.
4. For certain restrained and all unrestrained floors, roofs and beams, the reinforcing steel temperature rises to 1100^{o}F.

The complete requirements of ASTM E 119 and the conditions of acceptance are much more detailed than summarized above. Experience shows that concrete floor/roof assemblies and walls usually fail by heat transmission (item 1); and columns and beams by failure to sustain the applied loads (item 3), or by beam reinforcement failing to meet the temperature criterion (item 4).

Advanced Analytical Models

Recently some engineers have suggested using 3D finite element software to calculate the change in spatial temperatures over time in structural components using as input the time, temperature, and pore pressure data from the fire analysis described in previous sections. The software has to be able to model the non-linear non-isotropic behavior of reinforcement steel and concrete including crack development and crushing of the concrete. In addition to the external service loads, the model has to be able to include the following: (1) internal forces due to restraints that prevent free expansion, (2) internal forces due to pore pressure changes, (3) internal forces due to redistribution due to degradation of the mechanical properties of the steel reinforcement and concrete, (4) internal forces due to second order effects from the interaction of external loads and the deformations due to the three types of internal forces mentioned above.

CTLGroup performed a 3D analysis using the software DIANA for the Portland Cement Association and was able to obtain a fair correlation to actual ASTM E119 tests on high strength concrete columns. Needless to say, this type of analysis is very complex and expensive and therefore is not suitable for general structural design.

ACI 216 Method

Although testing according to ASTM E 119 is probably the most reliable method, the time and expense required to build and test the assemblies makes this method impractical and is actually unnecessary for most situations. The methods contained in ACI 216.1 (2) are based on fire research performed from 1958 through 2005 and are by far the most commonly used in typical design situations. The fire resistance (based on the heat transmission end point) of a concrete member or assembly is found by calculating the equivalent thickness for the assembly and then finding the corresponding rating in the charts and tables provided. The equivalent thickness of solid walls and slabs with flat surfaces is the actual thickness. The equivalent thickness of walls and slabs that have voids, undulations, ribs, or multiple layers of various materials (for example, a sandwich of concrete, insulation, and concrete) must be calculated using equations found in ACI 216.1.

An analytical method of calculating fire resistance for flexural members is contained in ACI 216.1 (4). This method involves estimating the actual temperatures of the concrete and reinforcing steel and using the properties of the materials at those temperatures in the analysis. The method assumes that the bottom, positive moment steel will reach elevated temperatures and begin to weaken before the top concrete and reinforcement. This allows the moment in the member to be redistributed from the weaker, positive moment region to the negative moment region where little reduction in strength will have occurred.

Once it is established that the member or the assembly has enough equivalent thickness to satisfy the heat transmission end point, it must also be determined whether there is enough cover on the reinforcing steel to prevent excessive heat from reducing the yield strength to the point where it can no longer carry the loads. The cover requirements for slabs are functions of the required fire rating, aggregate type, restrained or unrestrained construction, and prestressed or non-prestressed reinforcement.

The Code Approach

State and municipal building codes throughout the country regulate the fire resistance of the various elements and assemblies comprising a building structure. Structural frames (columns and beams), floor and roof systems, and load bearing walls must be able to withstand the stresses and strains imposed by fully developed fires and carry their own dead loads and superimposed loads without collapse for the specified duration. The 2006 International Building Code (IBC) (1) contains prescriptive requirements for building elements in Section 720. This section contains tables describing various assemblies of building materials and finishes that meet specific fire endurance ratings. The tables in the 2006 IBC are compatible with the tables in ACI 216.1 except for the provisions for the use of high strength concrete columns found in ACI 216.1-07.

Thickness Requirements

Test results show that fire resistance in concrete structures will vary in relation to the type of aggregate used. Table 1 shows a summary of the minimum thickness requirements for floor slabs and cast in place walls for different concrete types and for different fire resistance ratings. Table 2 summarizes the minimum column dimensions for different concrete types and different fire resistance ratings. Tables 1 and 2, show that there may be economic benefits to be gained from the selection of the type of concrete to be used in construction. The designer is encouraged to evaluate use of the alternative materials.

Cover Requirements

Another factor to be considered in complying with fire-resistive requirements is the minimum thickness of concrete cover for the reinforcement. The concrete protection specified in ACI 318 for cast-in-place concrete will generally equal or exceed the ACI 216.1 minimum cover requirements, but there are a few exceptions at the higher fire ratings. The minimum concrete cover to the positive moment reinforcement is given in Table 3 for one-way or two-way slabs with flat undersurfaces. The minimum concrete cover to the positive moment reinforcement (bottom steel) in reinforced concrete beams is shown in Table 4.

Conclusion

Concrete's excellent fire resistance has been proven by many tests performed for over 60 years. The American Concrete Institute and various building codes have developed prescriptive and analytical methods based on the fire tests on concrete components of structures. These methods provide architects and engineer a relatively easy way to select member proportions and reinforcement requirements for all but the very unusual structures. For the very unusual structures, alternate methods are available to adequately model or to test the complex behavior of reinforced concrete components subject to fire.

References

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3. ASTM E 119-00a, "Standard Test Methods for Fire Tests of Building Construction and Materials," ASTM International, West Conshohocken, PA, 2000, 21 pp.

4. JACI Committee 216R, "Guide for Determining the Fire Endurance of Concrete Elements," American Concrete Institute, Farmington Hills, MI, 2001, 48 pp.

5. Lotfi, Hamid and Munshi, Javeed, "Preliminary Analytical Investigation of High Strength Concrete Column Structural Performance Under Fire Loading" unpublished report, Construction Technologies Laboratories, Inc. June 2001

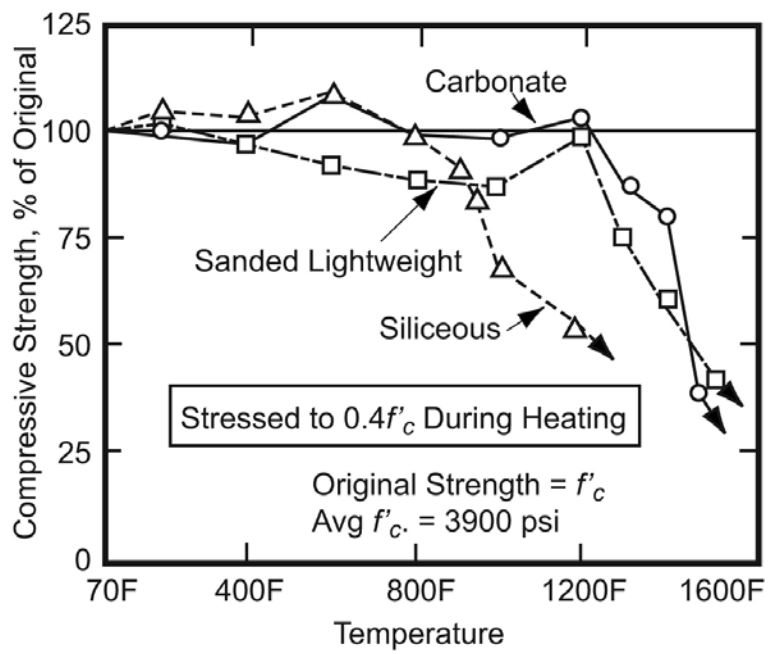

Figure 1 Effect of high temperature on the compressive strength of concrete

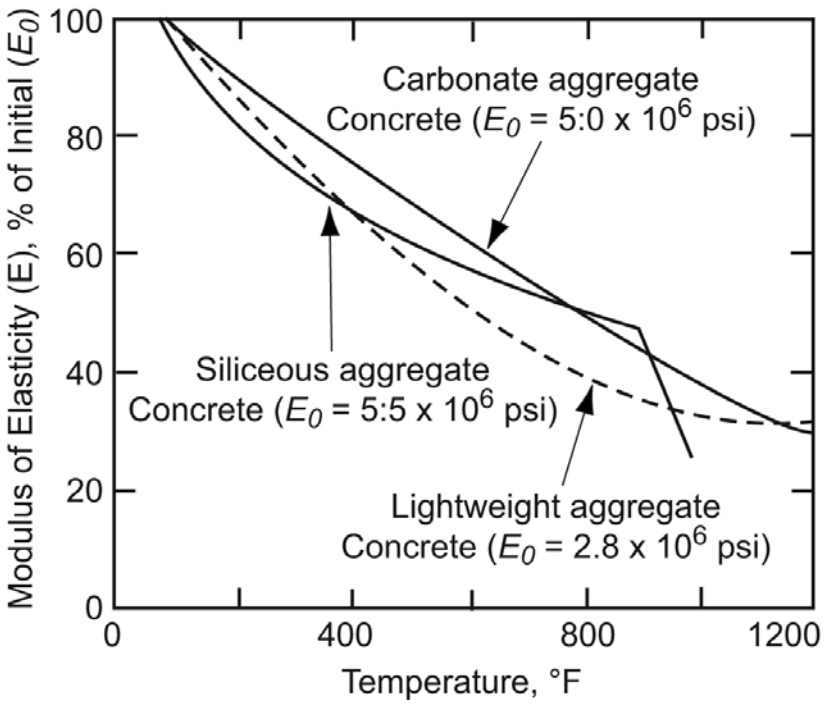

Figure 2 Effect of high temperature on the modulus of elasticity of concrete

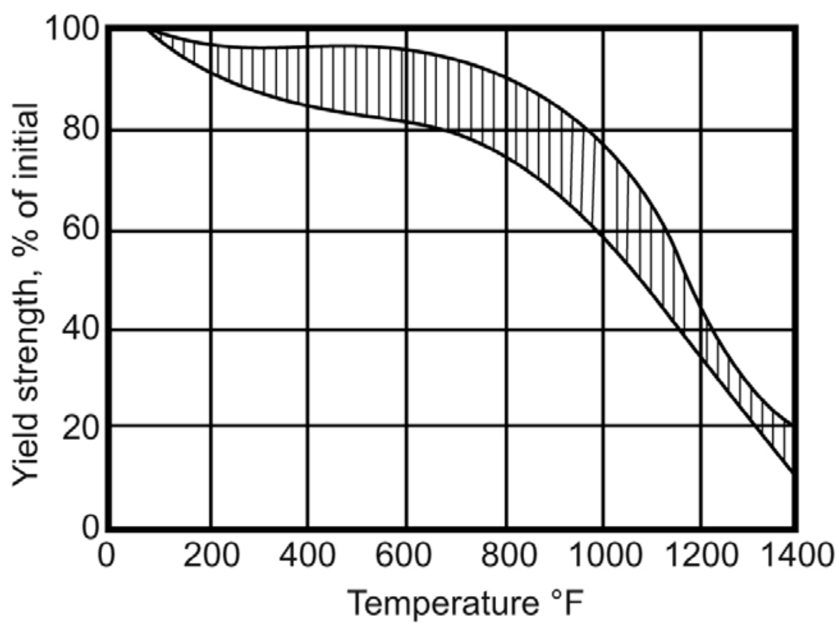

Figure 3 Effect of high temperature on the yield strength of steel

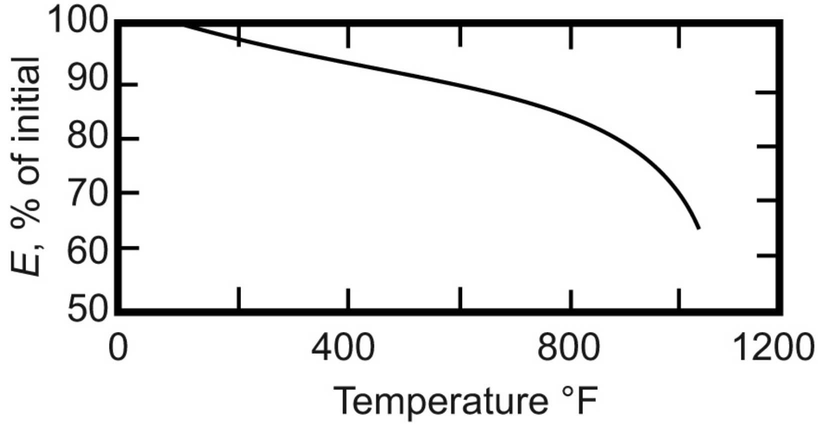

Figure 4 Effect of high temperature on the modulus of elasticity of steel

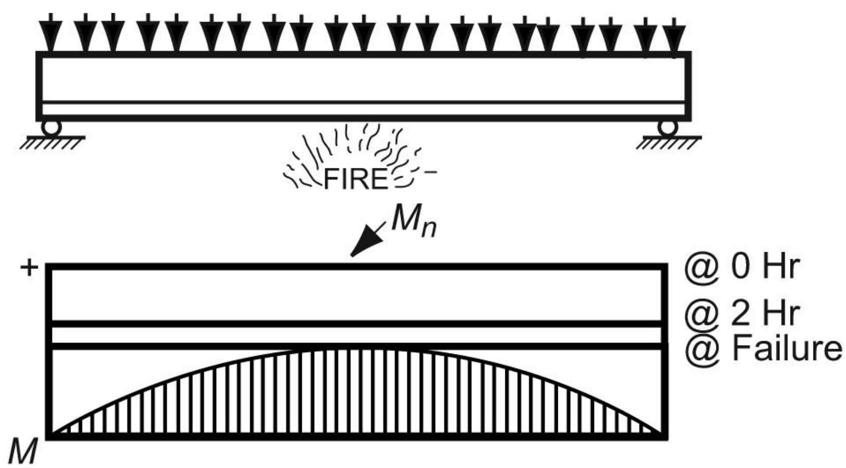

Figure 5 Effect of fire on the resistance of a simply supported reinforced concrete slab

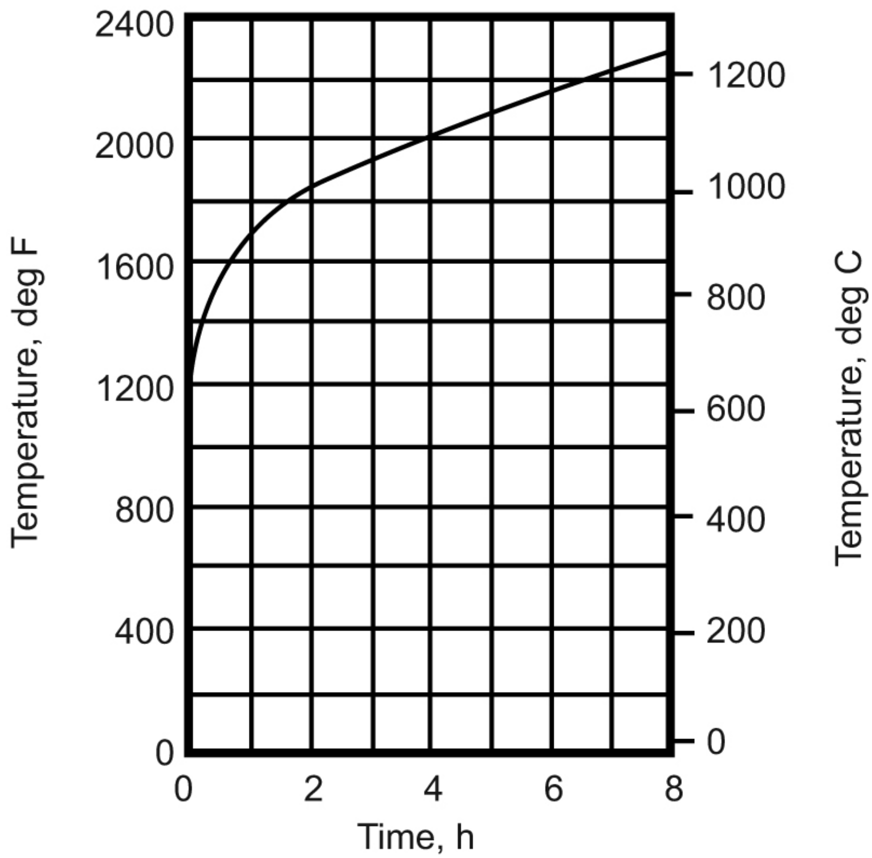

Figure 6 ASTM E 119 Time temperature curve

Table 1 Minimum thickness for cast in place floor and roof slabs, in.

	Fire resistance rating				
Concrete type	1 hr.	1.5 hr.	2 hr.	3 hr	4 hr.
Siliceous aggregate	3.5	4.3	5.0	6.2	7.0
Carbonate aggregate	3.2	4.0	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

Table 2 Minimum concrete column dimensions, in.

	Fire resistance rating				
Concrete type	1 hr.	1.5 hr.	2 hr.	3 hr	4 hr.
Siliceous aggregate	8	9	10	12	14
Carbonate aggregate	8	9	10	11	12
Sand-lightweight	8	8.5	9	10.5	12

Table 3 Minimum cover for floor and roof slabs, in.

	Fire resistance rating					
	Unrestrained					Restrained
Concrete type	1 hr.	1.5 hr.	2 hr.	3 hr	4 hr.	4 hr. or less
Siliceous aggregate	0.75	0.75	1	1.25	1.625	0.75
Carbonate aggregate	0.75	0.75	0.75	1.25	1.25	0.75
Sand-lightweight	0.75	0.75	0.75	1.25	1.25	0.75

Table 4 Minimum cover requirements to main reinforcement in beams (All types), in.

		Fire resistance rating				
Restrained or unrestrained	Beam width, in.	1 hr.	1.5 hr.	2 hr.	3 hr	4 hr.
Restrained	5	0.75	0.75	0.75	1	1.25
	7	0.75	0.75	0.75	0.75	0.75
	≥ 10	0.75	0.75	0.75	0.75	0.75
Unrestrained	5	0.75	1	1.25	-	
	7	0.75	0.75	0.75	1.75	3
	≥ 10	0.75	0.75	0.75	1	1.75

* Minimum cover for reinforcement in columns, for all aggregate types, is the smaller of, 1 in. times the number of hours of required fire resistance, or 2 in. (Reference 1)