



FIRE RESISTANCE OF ESCS STRUCTURAL LIGHTWEIGHT CONCRETE

Tech Note #16



Expanded Shale, Clay and Slate Institute
Rotary Kiln Structural Lightweight Aggregate



Chapter 7 of the International Building Code (IBC) contains requirements for materials and assemblies used for structural fire resistance and fire-rated separations of adjacent spaces. IBC-approved methods for determining the fire resistance ratings of concrete and masonry assemblies are found in “Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies”, ACI/TMS 216.1 (the Standard). The 1997 edition of the Standard is referenced in the 2003 and 2006 IBC for concrete and masonry materials. The 2007 edition of the Standard is referenced in the 2009 IBC. The current edition of the Standard was published in 2014. IBC Sections 721.3 through 721.5 are nearly identical to the provisions of the Standard.

Because full-scale fire testing of representative test specimens is not practical in daily practice due to time and financial constraints, the IBC outlines multiple options for determining fire ratings:

- standardized calculation procedures, such as those in the Standard and in Section 721 of the IBC,
- prescriptive designs such as those in Section 720 of the IBC,
- third party listing services, such as Underwriters Laboratory,
- engineering analysis based on a comparison with tested assemblies, and
- alternative means approved by the building official per Section 104.11 of the IBC and Section 1.2 of the Standard.

The calculation method is an economical and commonly used method of determining concrete and masonry fire resistance ratings. The calculations are based on extensive research, such as the Expanded Shale, Clay and Slate Institute (ESCSI) research program described below,

which established relationships between the physical properties of materials and the fire resistance rating. The calculation method is fully described in the Standard and IBC Section 721, and determines fire resistance ratings based on the solid thickness or equivalent solid thickness of concrete elements and the aggregate types used in their manufacture.

For prescriptive designs, the IBC and the Standard provide tables of the requirements of various assemblies to meet the fire resistance ratings specified. Table 1 duplicates one such table.

Private commercial listing services such as Underwriters Laboratory, allow the designer to select a fire rated assembly that has been previously tested, classified and listed in a published directory of fire rated assemblies.

The last two options in the bulleted list above require justification to the building official that the proposed design is at least the equivalent of what is prescribed in the code.

Table 1 - Fire resistance of single-layer concrete walls, floors, and roofs¹

Concrete and Aggregate Type	Minimum equivalent thickness for fire-resistance rating, in.				
	1 hour	1½ hours	2 hours	3 hours	4 hours
NWC with Siliceous Aggregate	3.5	4.3	5.0	6.2	7.0
NWC with Carbonate Aggregate	3.2	4.0	4.6	5.7	6.6
Semi-Lightweight Concrete	2.7	3.3	3.8	4.6	5.4
All-Lightweight Concrete	2.5	3.1	3.6	4.4	5.1

Adapted from ACI 216.1-14



ESCSI FIRE TEST PROGRAM

Throughout the 1960s, ESCSI conducted floor slab fire tests designed to determine the relationship between slab thickness and fire endurance based on heat transmission through the slab. The work included small-scale (pilot) and full-scale tests of structural lightweight concrete made with many different rotary kiln aggregates. This Information Sheet presents the results of these tests and brief discussions of related information, including the fire resistance values recognized by the IBC model building code.

Fire Testing

Fire testing in the United States and Canada is conducted in accordance with the "Standard Test Methods for Fire Tests of Building Construction and Materials," ASTM E119. The purpose of this test method is to compare the fire resistance properties of materials and assemblies in order to classify walls, columns, floors and other building elements under a specified laboratory exposure condition. The building code then specifies minimum construction types and fire resistance ratings to provide constructions that are safe, that are not a menace to neighboring structures nor to the public, and that offer reasonable protection to fire fighting personnel and equipment.

Concrete Properties

Prior to the 1950s, lightweight concrete was produced using lightweight coarse and fine aggregates, with no normalweight aggregate ("all-lightweight concrete").

Beginning in the 1950s, primarily for reasons of economy, concrete producers began to replace part or all of the lightweight fine aggregate with normalweight sand. Today, the typical practice in most of the United States and Canada is to make lightweight concrete using normalweight sand as the fine aggregate with coarse lightweight aggregate or "sand-lightweight concrete." In some regions "inverted mixes" or "reverse mixes," which are made with normalweight coarse aggregate and lightweight fine aggregate (and sometimes including some normalweight sand), are used for a variety of reasons. These "inverted mixes" are combined with sand-lightweight concrete into a single category in the Standard, which is classified as "semi-lightweight" concrete.

Table 2 presents the results of ESCSI's fire tests on 22 concrete slabs between 1960 and 1970. Except for the two prestressed concrete elements (Tests 5 and 6), all concretes listed in Table 2 were proportioned for a 3,000-psi specified compressive strength, with a 3- to 4-inch slump and approximately 6 percent entrained air. The cement contents ranged from 470 to 570 pounds of cement per cubic yard of concrete. For the prestressed concrete tests, the cement contents were higher to meet higher specified compressive strengths.

About 36 percent of the tests were conducted on lightweight concrete specimens containing lightweight coarse aggregate and normalweight sand replacing all or part of the lightweight fine aggregate. Table 2 lists the densities of the concretes used in the tests and indicates those containing normalweight sand. In all cases the concretes



with normalweight sand contained a minimum of 10 cubic feet by absolute volume of lightweight aggregate. These tests confirmed that the replacement of lightweight fines with normalweight sand results in a reduction in fire endurance.

Test Methods

All full-scale tests followed ASTM E119 with the floor slabs loaded to the prescribed superimposed loads. The pilot, or small-scale, tests had surface areas of less than 180 ft² and were tested with no superimposed loads. In all cases the slabs were at an equilibrium internal relative humidity of approximately 60 percent to 74 percent at the time of test. The endpoint of all tests was determined by heat transmission through the slab*.

**There are three failure criteria in ASTM E119: 1) Heat transmission – the temperature rise of the side of the assembly not exposed to fire exceeds the specified limit; 2) Structural collapse – the assembly fails to support the specified superimposed loads (if any) or self-weight of the structure; 3) Ignition of cotton waste – flames or hot gases escape through cracks or fissures in the assembly igniting cotton waste attached to the unexposed side. The time at which any of these criteria is met, the test is ended, setting the fire endurance of the assembly.*

Results

The results of these investigations are presented in Table 2 and are plotted in Figure 1 according to the type of fine aggregate (normalweight sand or lightweight) and type of test (full scale or pilot).

Comparison of Test Results and Building Code Requirements

The Standard and the IBC list the minimum concrete thicknesses required for a particular fire resistance rating, depending on the type of aggregate used in the concrete. These requirements are listed in Table 1 and are plotted as curves in Figure 1 the ESCSI fire test results for all-lightweight and sand-lightweight concrete.

Note that floors are tested in a horizontal position in ASTM E119, compared to an upright position for wall tests. In each test, the terminal temperature is reached across a concrete assembly without structural failure, passage of flames or the failure of the hose stream test. Wood or metal stud assemblies typically suffer structural failure under test conditions. Because the fire test results are similar for both horizontal and vertical constructions of monolithic concrete, the Standard and IBC require the same thickness for both concrete walls and floors, assuming a given aggregate type and fire resistance rating.





FIRE RATINGS OF OTHER CONCRETE ASSEMBLIES

Concrete Masonry Walls

The ratings discussed above apply only to monolithic concrete slabs and are generally not applicable to other concrete products such as concrete masonry, precast/prestressed single or double tees, or hollow-core concrete planks.

Concrete masonry is assigned a fire resistance rating by the Standard and by IBC based on aggregate type and the equivalent solid thickness (usually referred to as “equivalent thickness”) of the concrete masonry unit.

As mentioned above, private commercial listing services, such as Underwriters Laboratories (UL), allow the designer to select a fire rated assembly that has been previously tested, classified, and listed in a published directory of fire rated assemblies. The listing service also monitors materials and production to verify that the concrete masonry units are and will remain in compliance with appropriate standards, which usually necessitates a premium price for units of this type. The system also is somewhat inflexible in that little variation from the original tested wall assembly is allowed, including unit size, shape, mix design, constituent materials, and even the plant of manufacture.

More information on concrete masonry fire ratings is contained in ESCSI’s Information Sheet #14, “Fire Resistance of ESCS Concrete Masonry,” as well as National Concrete Masonry Association (NCMA) TEK 07-01D, “Fire Resistance Ratings of Concrete Masonry Assemblies”.

Precast, Prestressed Concrete

The IBC allows several approaches to determine the fire

resistance of precast, prestressed concrete elements and includes prescriptive “deemed-to-comply” criteria. Therefore, the IBC provides relatively simple and universally accepted fire design criteria. The Precast/Prestressed Concrete Institute (PCI) publishes *Design for Fire Resistance of Precast/Prestressed Concrete* (MNL-124) to explain many of the criteria included in the IBC. It also provides an alternate design approach, commonly referred to as rational design, when the prescriptive requirements of the IBC cannot be met. Manufacturers of precast, prestressed concrete products, such as single and double tees and hollow-core concrete planks, often have their products classified and listed by UL. UL publishes an annual *Fire Resistance Directory* which lists the producers’ names and the specifications for their concrete products which have the assigned fire resistance ratings.

Floor-ceiling assemblies

UL’s *Fire Resistance Directory* also lists many lightweight and normalweight concrete floor-ceiling assemblies which have been tested and assigned a fire resistance rating. These assemblies are typically concrete floors in steel frame buildings, where the assembly tested includes concrete placed on ribbed metal decking supported by steel beams or bar joists. Because there are many possible combinations of design elements, each unique assembly design has been fire-tested and assigned its own fire resistance rating.

When lightweight concrete is placed in a 1½ inch thickness on wood joist floors, fire ratings of one hour or more are normally achieved, depending on the thickness of the gypsum wallboard typically used as the bottom layer(s) of the floor-ceiling assembly. These designs are not listed in the UL *Fire Resistance Directory*, but generic lightweight concrete is included in several floor-ceiling designs listed in the *Fire Resistance and Sound Control Design Manual* GA-600-2018 published by the Gypsum Association.

CALCULATED FIRE ENDURANCE

IBC and the Standard allow analytical calculation methods to be used to determine the fire endurance of concrete with a single, complex cross-section as well as multi-wythe walls that contain concrete or concrete products. The reader is referred to the Standard for details of the calculation methods.

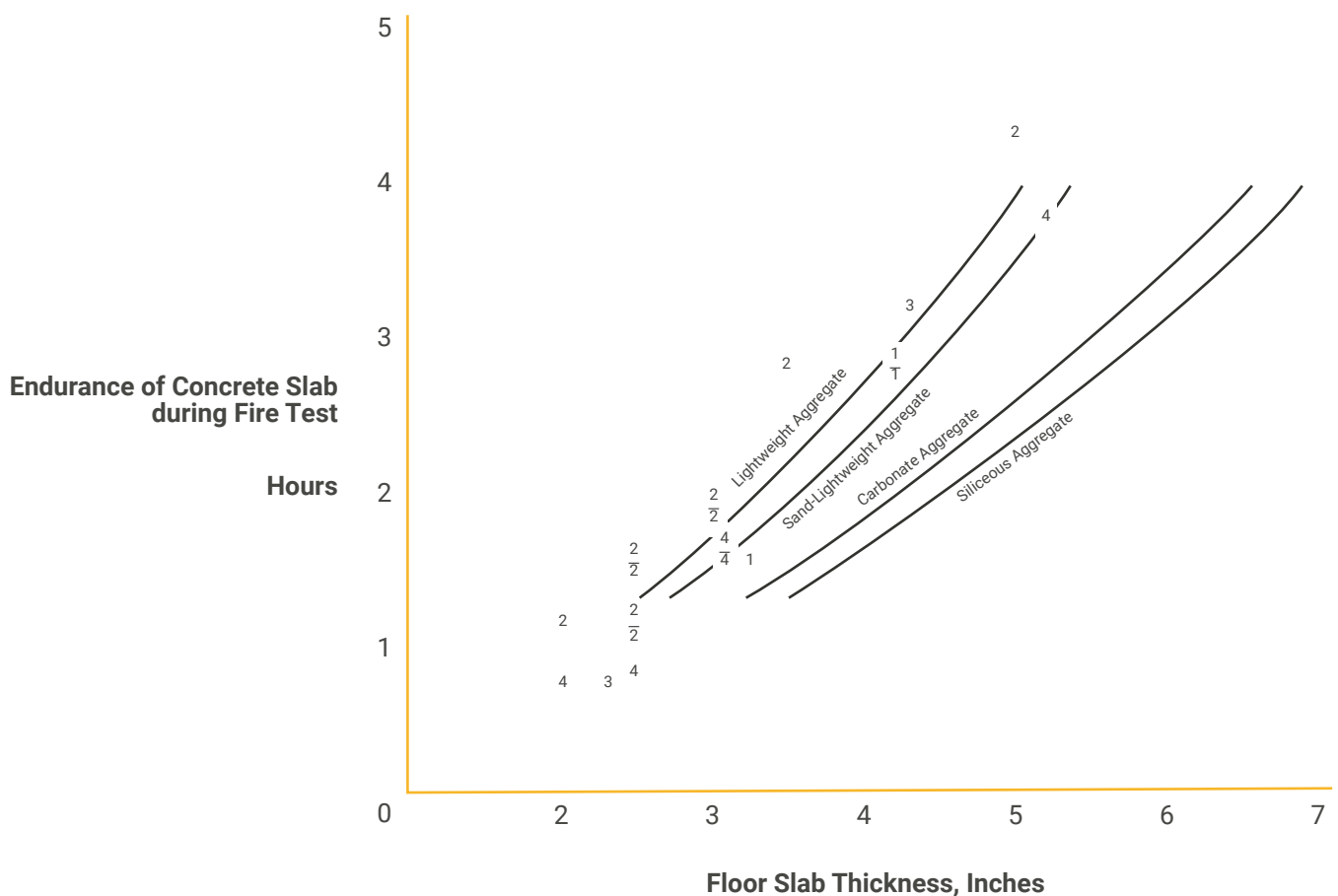
Figure 1 - Structural Lightweight Concrete Floor Slab Fire Tests²

Legend

- 1 - All Lightweight Concrete, Full Scale
- 2 - All Lightweight Concrete, Pilot Scale
- 3 - Sand-Lightweight Concrete, Full Scale
- 4 - Sand-Lightweight Concrete, Pilot Scale

Fire Test Results

Curves Indicate Code Requirements



Source: *Lightweight Concrete Information Sheet* Revision 9/88, "Fire Resistance of Expanded Shale Clay and Slate Structural Concrete Slabs," Expanded Shale Clay and Slate Institute

Table 2 - Fire Test Results

Test No.	Year	Lightweight Aggregate	Fine Aggregate Type	Slab Thickness, in	UNIT WEIGHT (pcf)			Time, min.	Test Scale	File No.
					Plastic	28 Days	At Test			
1	1960	Z	LW	2.5	98.5	94.2		68	Pilot	
2	1960	Z	LW	5.0	98.5	94.2		262	Pilot	
3	1961	X	LW	2.5	104.8	99.8		55	Pilot	
4	1961	Z	LW	2.5	98.4	96.8		58	Pilot	
5	1961	X	NW	4.5		108.0*		190	Full	PCI-UL R4123-5-7-8
6	1962	Z	LW	4.0		95.0*		140	Full	PCI-UL R4123-9
7	1963	Z	LW	4.03		95.0*		141.75	Full	PCA S-14
8	1963	Z	LW	3.25		95.0*		82.5	Full	PCA S-15
9	1963	Z	LW	5.25	100.0	95.0*		304	Full	UL R-3746
10	1964	X	NW	3.0		107.8	106.4	79	Pilot	
11	1964	X	LW	3.0		97.8	96.2	88	Pilot	
12	1964	X	LW	2.5		97.5	96.5	68	Pilot	
13	1964	Y	NW	3.0	118.6	117.4	116.6	76	Pilot	
14	1964	Y	LW	3.0	110.0	107.7	106.0	97	Pilot	
15	1964	Y	NW	3.0	117.0	115.3	114.4	84	Pilot	
16	1964	Y	NW	2.5	119.0	118.0	116.0	47	Pilot	
17	1967	T	NW	2.0	117.6	114.0		41	Pilot	
18	1967	T	NW	5.18	117.6	114.0		222	Pilot	
19	1967	U	LW	2.0	86.0	79.0		61	Pilot	
20	1967	U	LW	3.46	86.0	79.0		165	Pilot	
21	1967	U	LW	5.0	86.0	79.0		368	Pilot	
22	1970	X	NW	2.3	109.0		106.0	41	Full	PCA S-46

LW = Lightweight Aggregate Fines

NW = Natural (or manufactured) normalweight fine aggregates

Time = Time at which the maximum temperature rise end point was reached.

* Estimated

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