Fire Resistance of Concrete Structures

Part 1: Walls

First of a two-part series on the technical aspects of fire resistance and concrete structural components

By Erin Ashley, NRMCA Director of Codes and Sustainability

Building codes require designers to provide fire protection for buildings by combining "active" fire protection systems with "passive" fire protections systems. Active fire protection systems include smoke detectors, sprinklers and other systems that activate in the presence of smoke or fire. Passive fire protection uses the building components and layout to reduce the risk and spread of fire by providing non-combustible fire rated walls, floors and roofs. These building components help to compartmentalize the building so a fire that starts in one part of a building does not spread to other parts of the building. The concept of combining active and passive fire protection systems is called balanced fire protection design. Implementing balanced fire protection design provides the highest achievable level of protection.

Balanced fire protection design is a relatively new concept in the construction industry. Before the advent of technology based active systems, fire protection for buildings relied almost exclusively on passive fire protection. However, as active fire protection systems were developed, the relative importance of passive systems for reducing smoke and fire spread through compartmentalization and fire resistant components has been slowly diminished in the building codes.

The primary goal of building codes is to protect public safety (life). While reliable active fire protection can achieve this goal, the additional advantage of passive systems in a balanced design is to minimize damage to the owner's property. In some opinions, this may go beyond the minimum standards for public safety that needs to be established in building codes, but it is clearly in the owner's interest to retain use of the structure after a fire. More recently, building codes have adopted the use of active fire protection features in lieu of non-combustible fire resistive construction. This concept is called "trade-off." Simply put, designers are permitted to reduce or "trade-off" the amount of passive fire protection by implementing additional active features. The concrete industry continues to oppose the trade-off concept and supports the balanced design concept. Without the balanced design approach, one relies solely on the effectiveness and reliability of a mechanical system to provide the needed fire protection for the building. Fire containment provides a reliable method to reduce the spread of fire and smoke even in the presence of mechanical system failure. For the building designer, fire containment can be provided through the use of fire resistive concrete walls, floors and ceilings. Although fire resistive containment and construction includes all structural members, the focus of this article will be on fire resistant concrete walls.

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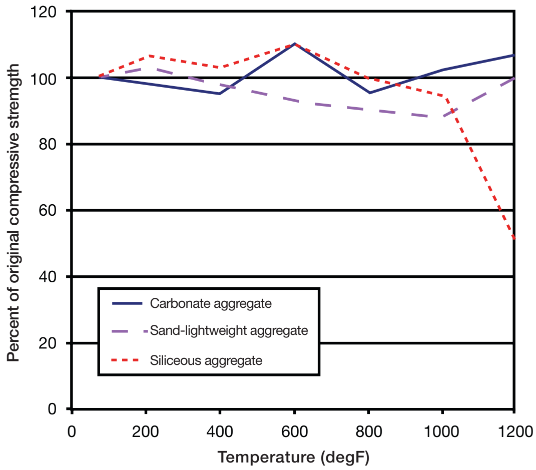

Figure 1. Strength temperature relationship for various aggregate types

The fire resistance of concrete walls is directly impacted by the choice of aggregate. Historically, concrete has performed well in large structural fires due to its noncombustibility and low thermal conductivity. The most common method of determining a structural member's performance in a fire is by a series of tests leading to a fire resistance rating. Fire resistance is defined as the ability of the structural member to withstand exposure to a fire without loss of load bearing function or ability to act as a barrier to spread a fire. The most common test method for determining fire resistance in the United States is the ASTM Standard E 119, *Test Methods for Fire Tests of Building Construction and Materials*. ASTM Standard method E 119 is a fire test that exposes the structural member to a standard fire on one side of the wall. For the structural member to pass the test, three criteria must be met – structural stability, integrity and temperature rise on unexposed face.

Concrete structural members tend to perform well in the ASTM E 119 test. However, unlike steel, the concrete fire resistance cannot be determined by calculating a single critical temperature. The temperature within the concrete member cross section is not uniform throughout the fire exposure; therefore, the thermal and mechanical properties of the concrete vary with time and location of fire exposure within the section. The calculation of fire resistance in concrete is further complicated by the wide range of aggregates and other properties of concrete used in the concrete member. Results of fire tests and fire ratings are very specific to the assemblies tested.

Aggregate can amount to 60-80% of the total volume of concrete; therefore, the choice of aggregate directly impacts the performance of concrete during a fire. As the temperature rises in a concrete wall, the strength of the wall is diminished. Figure 1 shows the strength temperature relationship for carbonate aggregate, sand-lightweight aggregate and siliceous aggregate. While the siliceous aggregate concrete strength is reduced by half at temperatures of 1200°F, the carbonate and lightweight aggregate concrete maintains near 100% of its original strength.

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In lieu of performing standard fire tests on walls, building codes permit designers to calculate the fire resistance rating using analytical methods. These would generally be more conservative than fire ratings obtained from fire tests. Two methods exist for determining the fire resistance of concrete walls: empirical or the more complicated analytical process. ACI 216.1-97, *Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*, provides a simplistic empirical method for determining fire resistance of concrete walls. Table 2.1 from ACI 216, reproduced here, provides the minimum equivalent thickness required of a concrete wall based on aggregate type to achieve a fire resistance rating of one hour to four hours. For solid flat concrete walls, the actual thickness is equal to the equivalent thickness. For walls that are more complex, such as cast-in-place walls that are not flat (varying thickness) and concrete masonry walls, the equivalent wall thickness is determined using formulas provided in ACI 216.1-97. A more complex analytical method for determining fire resistance of a concrete wall, with examples, is provided in ACI 216R, *Guide for Determining the Fire Endurance of Concrete Elements*.

As seen in Table 2, the use of structural lightweight concrete can significantly improve the fire resistance of concrete walls as can be observed from the reduced thickness required for the same fire rating compared to concrete with normal weight aggregate. Concrete walls using lightweight aggregate maintain between 90-100% of their original compressive strength at tem-

ACI 216.1-97 Table 2.1. Fire Resistance of singular layer concrete walls, floors, and roofs

Aggregate Type	Minimum equivalent thickness for fire resistance rating, in 1 hr	1.5 hr	2 hr	3 hr	4 hr
Siliceous	3.5	4.3	5.0	6.2	7.0
Carbonate	3.2	4.0	4.6	5.7	6.6
Semi-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

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peratures exceeding 1000ºF due to the low thermal conductivity of the lightweight aggregate. Due to the slow temperature rise of concrete members, the minimum required thickness to achieve a particular fire resistance is decreased; therefore, less concrete is needed to achieve the equivalent fire performance of normal weight concrete.

The thermal conductivity of concrete is temperature dependent and varies based on the type of aggregate. Figure 2 shows a comparison of the thermal conductivity of concrete based on aggregate type 1.6 W/mK for siliceous concrete, 1.3 W/mK for calcareous concrete and 0.8 W/mK for lightweight concrete. Thermal conductivity is described in units Watts per meter Kelvin (W/mK), and is defined as the quantity of heat, *W*, transmitted in time through a thickness, m, in a direction normal to a surface, due to a temperature rise, K. Lightweight aggregate has low thermal conductivity due to the high temperature manufacturing process, which expands the aggregate and imparts air voids into the concrete. Simply put, the lower the thermal conductivity of the concrete, the slower the concrete will rise in temperature when exposed to a fire. The low temperature rise of concrete provides the material's exceptional strength during a fire event.

The fire resistance of concrete assumes that all concrete remains in place during the fire event. The beneficial properties of concrete in a fire are reduced if concrete spalls during elevated temperatures. The spalling phenomenon is not well understood but conventional theory states that spalling is chiefly caused by the increase in water vapor during elevated temperatures. If the concrete cannot naturally dissipate the pressure increase due to the increase in water vapor, the pressure exceeds the tensile strength of the concrete and spalling occurs. It could be related to a difference in the coefficient of thermal expansion of the aggregate relative to the cement paste. In that sense, carbonate aggregates are more compatible with cement paste than siliceous aggregate. In some cases, the chance of spalling can be reduced based on the choice of aggregate. High strength concrete tends to be more susceptible to spalling due to its reduced pore volume and low diffusion of water vapor during elevated temperatures. Research at NIST has demonstrated that high strength concrete with synthetic fibers will have reduced spalling because as fibers melt, they provide paths for vapor to escape. Lightweight concrete is less susceptible to spalling due to its increased permeability, which allows water vapor to expand into voids, thus relieving internal stresses.

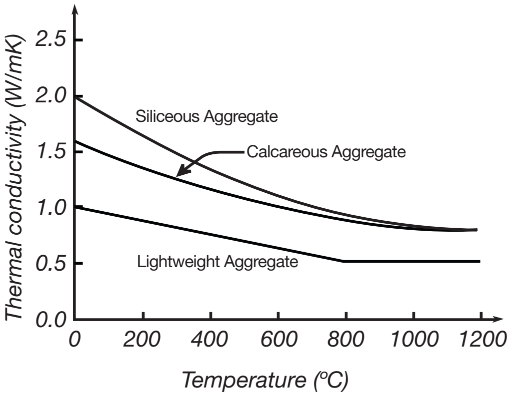

Figure 2. Thermal conductivity of concrete based on aggregate type

Concrete construction provides an excellent means for achieving the required fire resistant rating required by code. The choice of aggregate determines the required thickness of the concrete wall to achieve the designated fire resistance rating. It's the designer's responsibility to select the minimum wall thickness to provide the appropriate fire resistance rating. However, the minimum thickness of the wall can change depending on the type of aggregate used in the concrete. Therefore, it is imperative that the concrete producer understand the impact of choice of aggregate on the fire resistant attributes of the building components. ■

Resources: Buchanan, A. *Structural Design for Fire Safety.* Wiley & Sons, New York, 2002.

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Erin Ashley is director of codes and sustainability for the National Ready Mixed Concrete Association. She provides technical support to NRMCA members and state affiliates regarding local building codes and standards and promotes the adoption of statewide minimum building codes. She represents NRMCA on various national building code committees and green building standard committees. Ashley provides education and training programs for concrete producers, contractors, engineers and architects with a focus on building codes and sustainability. She is a doctoral candidate in reliability engineering at the University of Maryland. She holds a Master of Science in Reliability Engineering and Bachelor of Science in Fire Protection Engineering from the University of Maryland.

For more information, contact Erin Ashley at eashley@nrmca.org.