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Thermal Performance of Concrete Masonry Walls in Fire

Originally published August 1971

T.Z. Harmathy and L.W. Allen

Please note

Concrete has long been recognized as a durable and versatile building material, and concrete masonry units are used widely in the construction of modern buildings. Exposure to elevated temperatures characteristic of those attained in fires, however, may induce marked changes in the thermal and rheological[*] properties of the component materials of concrete. Because of this, attention has been focused for some time on the behaviour of masonry units under unusual circumstances such as those experienced during fires. Concrete performance in fire is the subject of this Digest.

Fire Endurance Tests

The fire resisting qualities of building elements are usually evaluated on the basis of standard fire endurance tests such as CSA B54.3 and ASTM E-119. These specifications require that a representative sample of the building element, an area at least 100 ft^2 for walls, be exposed on one side to the atmosphere of a specially built test furnace in which temperature is controlled to follow a prescribed curve representing, in an idealized way, the temperature in a burning room. The other side of the sample remains at all times in contact with the cooler ambient atmosphere. The test specimen is deemed to have failed if the temperature on the cool side rises 250°F deg above the initial level or if the wall ceases to function structurally as an effective barrier against the spread of fire. The time of failure is referred to as the construction's "standard fire endurance."

With masonry walls the possibility of structural failure is minimal so that research has been mainly concerned with the thermal fire endurance and the [actors that affect it, that is, with the thermal properties of concrete and the geometry of the masonry units.

Characteristics of Cement Paste

Typical concretes contain roughly 25 per cent (by volume) cement paste and 75 per cent aggregate. In spite of its relatively small proportion the cement paste is the component that influences the properties of concrete most and in many respects makes it a unique building material. More than half of a mature cement paste consists of an impure calcium silicate hydrate, commonly referred to as tobermorite gel. This gel is characterized by a very low degree of crystalline order (having a somewhat indefinite microstructure) and has extremely large internal surface areas. These enable concretes to hold large amounts of moisture in equilibrium with normal atmospheric conditions.

In tobermorite gel, coarser but still very small crystals of calcium hydroxide and a number of other more or less crystalline compounds are embedded. As the concrete is heated, the moisture held in the pores of the paste escapes. Dehydration of the tobermorite gel starts at around 200°F and continues uninterrupted to about 1600°F. Superimposed on this process is the dehydration of calcium hydroxide, which takes place at about 800°F.

Desorption of moisture and all dehydration reactions involve the absorption of heat and retard the flow of heat through the construction. These latent heat effects greatly improve the performance of concrete as a fire resistant building material.

Autoclaving

During the manufacture of concrete masonry units, setting and hardening of the cement paste can be accelerated by raising the temperature. To avoid loss of pore water necessary for hydration, steam is used for heating, either at atmospheric pressure or at 100 to 200 $lb/in.^2$. If elevated pressure is applied, it is usual to add fine quartz to the cement and the process is referred to as autoclaving. In this process quartz reacts with the cement to form crystalline tobermorite instead of tobermorite gel. There is almost no calcium hydroxide in autoclaved pastes.

As the internal surface area in crystalline tobermorite is relatively small, autoclaved products hold less moisture than non-autoclaved concretes. In addition, the thermal conductivity of crystalline tobermorite is somewhat higher, so that autoclaving does not offer any advantage from a fire endurance point of view. It is, nevertheless, widely used in the industry because it results in higher strength and greater dimensional stability. Building codes do not generally recognize any distinction between the performance in fire of autoclaved and non-autoclaved concrete masonry units.

Aggregates

Although latent heat effects (heats of desorption, dehydration) are primarily determined by the cement paste, the thermal conductivity of concrete is determined by the aggregate.

Concretes may be divided into two major groups: normal weight concretes (usual density range: 120 to 140 lb/ft^3) and lightweight concretes (75 to 100 lb/ft^3). Normal weight concretes are usually made with natural deposits of gravel and sand aggregates or with crushed stone. The two main factors that determine their value in fire are their chemical stability and degree of crystalline order. Less stable aggregates, i.e. those containing large amounts of hydrated water, undergo decomposition and dehydration reactions at higher temperatures. (In general, concretes that do not show more than 5 per cent weight loss when heated from 200 to 1600°F can be regarded as made with physicochemically stable aggregates.) As these reactions are normally accompanied by the absorption of latent heat, unstable aggregates are often an advantage from a fire endurance standpoint.

The thermal conductivity of aggregates, and thus of concretes made with them, depends on both the aggregate's internal microstructure and its mineralogical composition. The conductivity of highly crystalline aggregates (i.e. those having a well defined microstructure) is high at room temperature and decreases with rise of temperature. Amorphous aggregates (e.g. traprock, basalt) exhibit low conductivity at room temperature; this increases slightly as the temperature rises.

Among the common natural stones, quartz has the highest conductivity. The thermal conductivity of concretes made with quartz aggregates may be as high as 1.5 Btu/hr ft °F at room temperature (in oven-dry condition). The lower limit for the conductivity of normal weight concretes made with other natural aggregates is about 0.7 Btu/hr ft °F. When the temperature rises, the difference diminishes, and at temperatures over 1400°F all normal weight concretes exhibit roughly identical conductivities, 0.7 to 0.8 Btu/hr ft °F.

Lightweight concretes are usually made with processed lightweight materials or industrial byproducts such as cinder, slag, and various expanded slags, shales, clays and slates. Less frequently, natural lightweight aggregates are used, for example pumice, scoria, volcanic cinder, tuff. Lightweight aggregates, particularly manufactured ones, exhibit high chemical stability at elevated temperatures, so that the only latent heat effects that must be considered are those associated with the dehydration of the cement paste.

Since the porosity of lightweight aggregates is high and the solid matrix normally on the amorphous side, the thermal conductivity of lightweight concretes is very low, typically 0.2 to 0.4 Btu/hr ft °F at room temperature. Again, this range of values decreases at elevated temperatures and, above 1400°F, 0.35 Btu/hr ft °F is a typical value.

It is becoming more and more popular to substitute sand in lightweight masonry units for some of the fine aggregates. Typically, 10 to 20 per cent of the total aggregate volume is replaced by sand to control the porosity, strength and texture of the units, to ensure good paste-to-aggregate bonds, and to eliminate certain production problems. Lightweight concretes made with natural sand exhibit characteristics between those of the lightweight and normal weight concretes.

Geometry of Masonry Units

Although hollow masonry units often have a very complicated geometry, four dimensions (Figure 1) are of primary importance from the point of view of fire endurance.

L over-all thickness

l face shell thickness

a web thickness (average of a_1 and a_2)

b web spacing (average of b_1 and b_2)

For practical reasons, fire performance requirements for hollow and solid masonry are expressed in most building codes in terms of a single parameter, λ, designated equivalent thickness. λ is the thickness that would be obtained from the same amount of material if the voids were eliminated from the inside of the units. The relation between λ and the above variables is

$$\lambda = 2l + a/b\ (L - 2l)$$

The equivalent thickness is usually determined experimentally but, as discussed in Reference (1), some of the experimental techniques are strongly misleading.

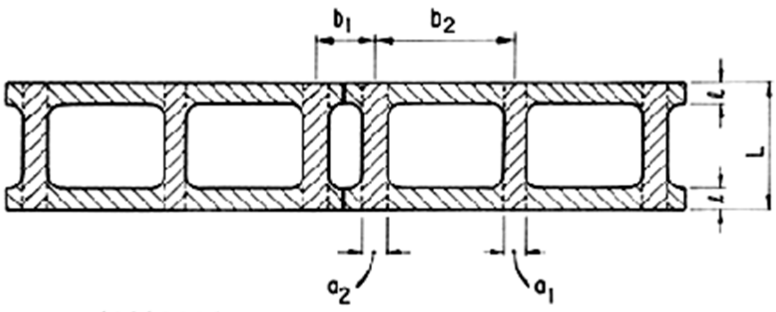

Figure 1. Geometry of Concrete Mansonry Units.

Fire Endurance Information

Hundreds of fire tests on concrete masonry units have already been performed (2). Based on these data, Supplement No. 2 to the National Building Code tabulates the minimum equivalent thickness requirements for masonry units made with different types of aggregate.

In correlating fire test data it is usual to derive the relation between thermal fire endurance and equivalent thickness from a log-log plot of the fire test results and to express the fire endurance in the form of a power law. Though such a relation may be convenient for practical application, in a strict sense it is inaccurate to use the equivalent thickness for correlating fire endurance data. To realize this, attention is directed to Figure 2. The sketches in this figure show three walls whose equivalent thicknesses are obviously equal. Owing to the additional resistance of an air layer to heat flow, the wall shown in Figure 2(b) will exhibit higher fire endurance than that shown in Figure 2(a). For similar reasons, the wall in Figure 2(c) will yield even better performance.

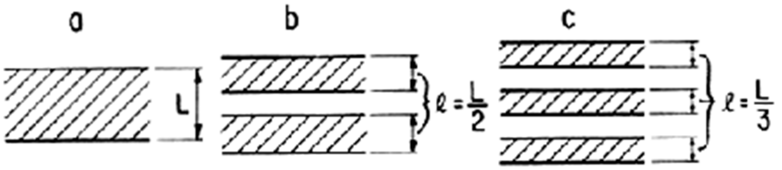

Figure 2. Illustration of the Fallacy of Equivalent Thickness Concept.

The gain in fire endurance resulting from the insertion of a 1-in. air gap may range as high as 10 per cent. As the coefficient of heat transfer through an air layer is practically independent of the thickness of the layer, this gain cannot be increased by increasing the distance between the layers.

To assume that fire endurance is directly related to the amount of solid material in the unit is only a rough approximation, but it is sufficiently accurate for application to the fire provisions of the National Building Code. As an aid to designers wishing to achieve optimum fire endurance periods for units made with a given amount of material, the results of a comprehensive study concerning the thermal performance of concrete masonry units may be useful (3).

In these numerical studies, involving over a thousand computer calculations, the complex geometry of the units and the temperature dependence of the thermal properties of the material were taken into account and great care was exercised to simulate the proper mechanisms of heat transport. Four different kinds of concrete were modelled in such a way that they could be regarded as representative of concretes exhibiting the poorest and best behaviour during fire in their respective normal weight and lightweight groups.

The most important conclusions of this study may be summarized as follows:

1. In the design of concrete masonry units for fire endurance it may be assumed, a) that hollow units are composed of solid sections of thickness L (see Figure 1) and of two-layer configurations (i.e. two layers of thickness *l* separated by an air gap); and b) that hollow units consist of solid and double-layer sections, the relative proportions of which are a/b and (1-a/b).
2. The fire endurance of both the solid sections and the two-layer configurations can be described in terms of the thermal conductivity and thermal diffusivity of the concrete at room temperature and L (for the solid sections) or *l* (for two-layer configurations) (see Figure 1 and Figure 2). These relations are specially suitable for extrapolation or interpolation purposes and for the design of economical masonry units. The Division of Building Research will be glad to describe the method of making the calculation to anyone interested.
3. A given amount of material is better utilized in the face shell than in the web.
4. The presence of air cavities (of any thickness) is more beneficial the higher the thermal conductivity of the concrete.

Effect of Moisture

The results of these computer calculations are applicable only to dry masonry walls. Because of the elaborate microstructure of tobermorite gel, ordinary (non-autoclaved) concrete products can hold large amounts of moisture in equilibrium with normal atmospheric conditions. The presence of moisture usually benefits fire endurance. In general, each 1 per cent increase of moisture (by volume) is capable of increasing the fire endurance by 4 to 5 per cent. Methods of calculating the fire endurance at some given moisture content, if the fire endurance in the dry condition is known, or vice versa, have been described elsewhere in detail (4).

Above a certain critical level, and depending on the porosity of the cement paste, moisture may cause explosive spalling in fire. If the initial moisture content is too high, a layer of concrete roughly 1 inch from the side exposed to fire becomes completely saturated with water and blocks the movement of water vapour towards the cooler side. The build-up of vapour pressure often results in violent disintegration of the construction. Older concretes and those made with low water-cement ratios are specially susceptible to explosive spalling.

The prediction of the fire endurance of masonry units by calculation only, without test, is still at an elementary stage. Despite this, recent improvements in the knowledge of the response of materials to fire, together with approximate calculation methods now available, can be very useful. It is possible to interpolate and extrapolate test results and in this way extend the range of masonry constructions to which they can be applied.

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4. Harmathy, T. Z. Effect of Moisture on the Fire Endurance of Building Elements. American Society for Testing and Materials STP 385, 1965, p. 74.

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* material characteristics associated with the deformation and flow of matter.