The Concrete Centre™

Concrete and Fire Safety

HOW CONCRETE CONTRIBUTES TO SAFE AND EFFICIENT STRUCTURES

Concrete and Fire Safety

Contents

Introduction

In fire, concrete performs well - both as an engineered structure, and as a material in its own right: this publication explains how. It is a useful reference guide for designers, clients, insurers and government bodies who need a summary of the important aspects of fire safety design, and the role that concrete can play in maintaining the integrity of the structure, thus preventing the spread of fire and protecting lives. Buildings are covered in depth, while reference is made to tunnels and other structures where concrete is also used.

It is important that we create buildings and structures that minimise risk to both people and property as effectively and as efficiently as possible. Because of concrete's inherent material properties, it can be used to minimise fire risk for the lowest initial cost while requiring the least in terms of ongoing maintenance.

In most cases, concrete does not require any additional fire-protection because of its built-in resistance to fire. It is a non-combustible material (i.e. it does not burn), and has a slow rate of heat transfer. Concrete ensures that structural integrity remains, fire compartmentation is not compromised and shielding from heat can be relied upon.

Protecting people and property

The role of fire safety standards

A study of 16 industrialised nations (13 in Europe plus the USA, Canada and Japan) found that the number of people killed by fires in a typical year was 1 to 2 per 100,000 inhabitants, while the total cost of fire damage amounted to 0.2 per cent to 0.3 per cent of GNP.

In the USA alone, statistics collected by the National Fire Protection Association for the year 2000 showed that more than 4,000 deaths, over 100,000 injuries and more than $10bn of property damage were caused by fire. UK statistics suggest that of the half a million fires per annum attended by firefighters, about one third occur in occupied buildings. These fires result in around 600 fatalities (almost all of which happen in dwellings). The loss of business resulting from fires in commercial and office buildings runs into millions of pounds each year.

The aim of design for fire safety is to ensure that buildings and structures are capable of protecting both people and property against the hazards of fires. Although fire safety standards are written with this express purpose, it is understandably the safety of people that assumes the greater importance. Appropriate design and choice of materials is also crucial in ensuring fire safe construction.

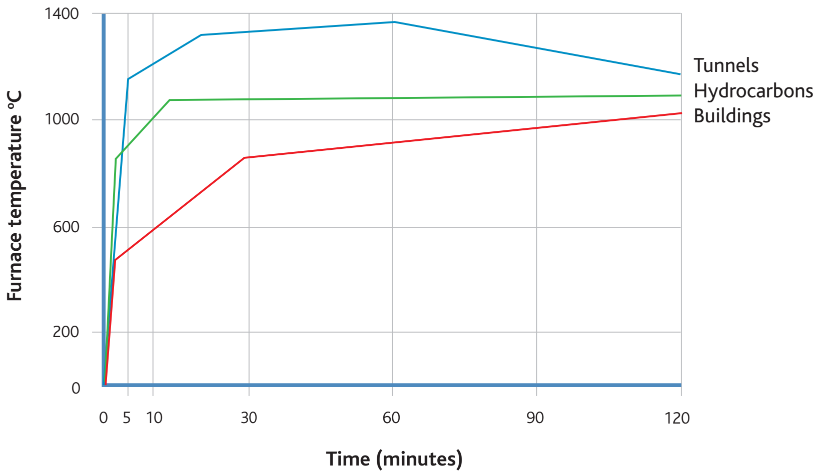
Standard testing methods are used to determine the fire performance of materials and building or structural elements. The tests may be either at a small scale (e.g. in a specially built oven/furnace) or at full-scale (i.e. on a part or whole mock-up of a building).

To enable comparison between tests, three standard temperature-time curves have been established. These are:

- Standard fire scenarios for buildings
  (ISO 834 or BS 476)
- Offshore and petrochemical fires
  (hydrocarbon test developed by Mobil)
- Tunnel fires
  (RWS, Netherlands and RABT, Germany).

Each option has a different (idealised) temperature-time curve appropriate to the conditions as shown in the graph below. Notice that the idealised temperature in a building fire rises much more slowly and peaks at a lower temperature than, for example, a hydrocarbon fire (for example, from burning vehicles) because there is generally less combustible material present.

Figure 1: Standard fire curves for three scenarios: tunnels, hydrocarbons and buildings



It is vital that buildings and structures are capable of protecting people and property against the hazards of fire: **concrete can play a major role in achieving this.**

Concrete as a material

Performance in fire

Fires require three components:

- **Fuel**
- **Oxygen**
- **Heat source**

Fires can be caused by accident, energy sources or natural means. The majority of fires in buildings are caused by human error or arson. Once a fire starts and the contents / materials in a building are burning, the fire spreads via radiation, convection or conduction, with flames reaching temperatures of between 600°C and 1,200°C. Harm to occupants is caused by a combination of the effects of smoke and gases, which are emitted from burning materials, and the effects of flames and high air temperatures.

Changes to concrete in a fire

Concrete does not burn – it cannot be 'set on fire' unlike other materials in a building and it does not emit any toxic fumes when affected by fire. It will also not produce smoke or drip molten particles, unlike some plastics and metals, so it does not add to the fire load.

Building materials can be classified in terms of their reaction to fire and their resistance to fire, which will determine respectively whether a material can be used and when additional fire protection needs to be applied to it. EN 13501-1 classifies materials into seven grades (A1, A2, B, C, D, E and F). The highest possible designation is A1 (non-combustible materials). In 1996 the European Commission compiled a binding list of approved class A1 materials, and this includes concrete and its mineral constituents.

Concrete fulfils the requirements of class A1 because it is effectively non-combustible (i.e. does not ignite at the temperatures which normally occur in fires).

For these reasons concrete is proven to have a high degree of fire resistance and, in the majority of applications, can be described as virtually 'fireproof'. This excellent performance is due in the main to concrete's constituent materials (cement and aggregates) which, when chemically combined within concrete, form a material that is essentially inert and, importantly for fire safety design, has relatively poor thermal conductivity. It is this slow rate of conductivity (heat transfer) that enables concrete to act as an effective fire shield not only between adjacent spaces, but also to protect itself from fire damage.

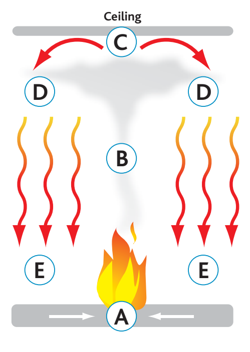
The rate of increase of temperature through the cross section of a concrete element is relatively slow. This means that the internal zones of the concrete do not reach the same high temperatures as a concrete surface exposed to flames. A standard ISO 834/BS 476 fire test on 160mm wide x 300mm deep concrete beams showed that after one hour of exposure on three sides a temperature of 900°C was reached on the surface of the concrete. However, at 16mm from the surface a temperature of 600°C was reached, whilst at 42mm from the surface the temperature had halved to just 300°C. This gave a decreasing temperature gradient of 300 degrees in only 26mm of concrete. When the concrete was below 300°C it fully retained its loadbearing capacity.

Even after a prolonged period of fire exposure, the internal temperature of concrete remains relatively low. This quality enables concrete to retain both its structural capacity and fire shielding properties as a separating element.

When concrete is exposed to high temperatures in a fire, a number of physical and chemical changes take place. These changes are shown in Table 1 opposite, which describes what happens to the material when it is heated to a particular temperature. The temperatures tabled are concrete temperatures, not flame or surface air temperatures.

Spalling is a phenomenon which may occur in particular circumstances in which the surface concrete breaks away at elevated temperatures. In normal buildings under normal fire loads it may not occur at all or is not of significance. However, if, there are concrete strengths above 60MPa, high moisture contents or particular aggregates then the likelihood of spalling increases. Designs allow for this in reinforcement detailing and/or the use of polypropylene fibres.

Figure 2: A standard compartment fire



A: Oxygen drawn in to feed fire

B: Smoke plume rising

C: If the flames reach the ceiling they will spread out and increase the heat radiation downward

D: Smoke layer forming below ceiling and descending

E: Heat radiated downward onto surface contents

Concrete does not burn, produce smoke or emit toxic vapours. It is an effective protection against the spread of fire due to its slow rate of heat transfer.

Concrete is a non-combustible material. A concrete element can be used effectively for simultaneous loadbearing, separation and fire-shielding solutions.

Table 1: Concrete in fire: physiochemical processes

Concrete temperature (°C)	What happens
550-600	Concrete experiences considerable creep and loss of loadbearing capacity. However, in reality, only the first few centimeters of concrete exposed to a fire will experience this; internally the temperature is well below this.
300	Strength loss starts, but in reality only the first few centimetres of concrete exposed to a fire will get any hotter than this. Internally the temperature is well below this.
250-420	Some spalling may take place, with pieces of concrete breaking away from the surface.

After the fire

Reductions in temperatures reached in the concrete can usefully be derived from observations. Often the duration, intensity and extent of a fire can be determined from eye-witness accounts. It may be sufficient to take 'soundings' on the damaged concrete to determine the degree of deterioration. A hammer and chisel can be used to indicate the 'ring' of sound concrete or the 'dull thud' of unsound material. Also the concrete aggregate changes to a pink/red colour at 300°C, the same temperature which indicates strength loss, thus a survey taking small cores can determine the extent of concrete which needs to be removed.

A structural evaluation should follow the material investigation and the method of repair determined. Repair of concrete exposed to high fire temperatures is often preferable to demolition and reinstatement for cost reasons. *Assessment and Repair of Fire Damaged Concrete Structures* [1] provides significant detail on this topic.

Concrete structures

Performance in fire

Concrete structures perform well in fire. This is because of the combination of the inherent properties of the concrete itself, along with the appropriate design of the structural elements to give the required fire performance and the design of the overall structure to ensure robustness.

Concrete structural elements

Fire performance is the ability of a particular structural element (as opposed to any particular building material) to fulfill its designed function for a period of time in the event of a fire. These criteria appear in UK and European fire safety codes. In Eurocode 2, the three possible functions of loadbearing capacity (R); flame-arresting separation (E) and heat shielding (I) are tabled below. Time periods are attributed to each of these to designate the level of fire performance for each function. For example R120 indicates that for a period of 120 minutes the element will retain its loadbearing capacity when exposed to fire.

Table 2: The three main fire protection criteria, adapted from Eurocode 2, Part 1-2 [2]

Designation	Fire limit state	Criterion
Resistance (R)* Also called: Fire resistance Loadbearing capacity	**Limit of load** The structure should retain its loadbearing capacity.	The loadbearing resistance of the construction must be guaranteed for a specified period of time. The time during which an element's fire resisting loadbearing capability is maintained, which is determined by mechanical strength under load.
Integrity (E)* Also called: Flame arresting separation Tightness	**Limit of integrity** The structure should protect people and goods from flames, harmful smoke and hot gases.	There is no integrity failure, thus preventing the passage of flames and hot gases to the unexposed side. The time during which, in addition to fire resistance, an element's fire separation capability is maintained, which is determined by its connections' tightness to flames and gases.
Isolation (I)* Also called: Fire shielding Heat screening Separation	**Limit of isolation** The structure should shield people and goods from heat.	There is no isolation failure, thus restricting the rise of temperature on the unexposed side. The time during which, in addition to both fire resistance and fire separation, an element's fire shielding capability is maintained, which is defined by a permissible rise in temperature on the non-exposed side.

*Note that the letters R, E, I are derived from French terms; they remain so in the Eurocode in recognition of the fact that they were first introduced in France.

The heat flow generated in concrete elements by fire produces differential temperatures, moisture levels and pore pressures. These changes affect concrete's ability to perform at the three limit states. As a structure must be designed to prevent failure by exceeding the relevant fire limit states, the following must be avoided:

- Loss of bending, shear or compression strength in the concrete.
- Loss of bond strength between the concrete and the reinforcement.

Therefore, for any element there are two key design considerations with respect to fire:

1. Overall dimensions, such that the temperature of the concrete throughout the section does not reach critical levels.

2. Average concrete cover, so that the temperature of the reinforcement does not reach critical levels (500°C for steel reinforcing bar and 350°C for pre-stressing tendons).

Accepted values for these dimensions have changed over time as a result of research and development, testing and observation of fire-affected concrete structures, with data for design becoming more accurate by providing additional information on:

- The effects of continuity
- Pre-stressed concrete
- Lightweight concrete
- Choice of aggregate
- Depth of cover

Tabulated values are available in the codes of practice. Alternatively more rigorous calculation methods are available to design elements for required fire resistance performance.

Background to code guidance

The background research and documentation for the concrete part of the Eurocode suite has been compiled in *From ENV to Eurocode 2 – An interactive library of draft and background documents*. This CD includes the information relevant to Eurocode 2 1-2 Design of Concrete Structures - structural fire design [3].

The background to the methods for establishing the fire resistance of concrete structures specified in the relevant parts of the UK concrete code BS 8110 has been compiled in reference 4. The work focused on the original research and test results underpinning the tabulated data in BS 8110 to assess the relevance of the approach to modern forms of concrete construction. This study is important as it brings together in one document a body of information covering test results and research carried out over a number of years.

The investigation showed that the experimental results used as the basis for developing the tabulated data in BS 8110 supported the provisions of the Code in relation to assumed periods of fire resistance. In many cases the provisions are very conservative, as they are based on the assumption that structural elements are fully stressed at the fire limit state. Further details of this work are given on page 12.

Whole building behaviour

Whilst code provisions consider structural elements in isolation, in reality elements interact with one another. The beneficial interaction of elements can result in structures being safer than as designed.

Where a concrete member, for example a slab, expands under high temperatures to push against its supports, a mechanical arching effect takes place within the slab. This can provide an alternative loadbearing path for the reinforced concrete structure. This compression action can greatly increase the load capacity of a slab.

Large scale testing has also improved the understanding of a phenomena known as tensile membrane action. If a slab is highly deformed due to fire, the reinforcement in both the top and bottom of the slab can act in tension as a catenary to transmit the loads back to the supports.

Structural fire engineering

The specialist discipline of structural fire engineering involves the knowledge of fire load, fire behaviour, heat transfer and the structural response of a proposed building structure. The application of structural fire engineering allows a performance based approach to be carried out which can allow more economical, robust, innovative and complex buildings to be constructed than those using the traditional prescriptive rules and guidance approach to fire design.

The growth of structural fire engineering as a discipline is in response to the savings which result from carrying out such structural fire calculations. However, it does have the potential to make future change of use of a building more difficult as there is less redundancy in the design.

The method allows flexibility to increase levels of safety by, for example, protecting the building contents, the superstructure, heritage, business continuity or corporate image. Due to the inherent fire resistance of concrete and masonry structures, they can be used effectively to increase the fire resistance of buildings above that required just for life safety.

Concrete structures remain stable during fire

In fire-safety design, the functions of a structural element can be designated as loadbearing, separating, and/or fireshielding (R,E,I). The elements are typically given a numerical value (in minutes, from 15 to 360) presenting the duration for which the element can be expected to perform those functions (see Table 2 for an explanation). In the event of a fire, the structure must perform at least to the level required by legislation. In addition, maintaining the stability of the structure for as long as possible is obviously desirable for survival, escape and firefighting. This performance is particularly important in larger complexes and multi-storey buildings.

Structural frames made of concrete are designed to satisfy this performance demand for overall stability in the event of a fire. Indeed, in many cases concrete structural frames will exceed performance expectations in the event of a fire. The combination of concrete's non-combustibility and low level of temperature rise means that a concrete structure will not burn, and its strength will not be affected significantly in a typical building fire. Furthermore, concrete's inherent fire resistance acts as long-lasting, passive protection. This means that concrete does not have to rely on active firefighting measures such as sprinklers for its fire performance or additional passive fire protection.

Concrete is easier to repair after a fire

The majority of concrete structures are not destroyed in a fire. One of the major advantages of using concrete in a structure is that it can usually be easily repaired after a fire, helping to minimise inconvenience and repair costs. The modest floor loads that are actually applied in most structures, combined with the relatively low temperatures experienced in most building fires mean that the loadbearing capacity of concrete is largely retained both during and after a fire. For these reasons often all that is required is a simple clean up. Speed of repair and rehabilitation is an important factor in minimising any loss of business after a major fire. These options are clearly preferable to demolition and reinstatement.

The impact of a major fire at Tytherington County High School, Cheshire was limited due to the fire resistance of the concrete structure. Rather than taking a year to be demolished and replaced, as was the case with an adjacent lightweight structure, the concrete classrooms were repaired ready for the following term.

Non structural concrete elements: compartmentation

Concrete protects against all harmful effects of a fire. As a material it has proved so reliable that it is commonly used to provide stable compartmentation in large industrial and multi-storey buildings. By dividing these large buildings into compartments, the risk of total loss in the event of a fire is virtually removed. Concrete floors and walls reduce the fire area both horizontally (through walls) and vertically (through floors). Concrete thus provides the opportunity to install safe separating structures in an easy and economic manner. Its inherent fire shielding properties do not require any additional fire stopping materials or maintenance.

The five requirements in Table 3 must be taken into account when designing a structure, and this is the foundation for design methods for structural elements in respect of fire safety in the Eurocodes (e.g. Eurocode 2 1-2 Design of Concrete Structures – structural fire design).

Precast walls form fire resistant compartmentation for this storage facility. Courtesy of BDV.

In this warehouse fire in France, the firefighters were able to shelter behind the concrete wall in order to approach the fire closely enough to extinguish the flames. Courtesy of DMB/Fire Press.

In many cases concrete structural frames **will exceed performance expectations in the event of a fire.**

Table 3: Concrete structural elements and concrete compartment walls

Objective	Requirement	Use of concrete
1. To reduce the development of a fire.	Walls, floors and ceilings should be made of a non-combustible material.	Concrete as a material is inert and non-combustible (class A1).
2. To ensure stability of the loadbearing construction elements over a specific period of time.	Elements should be made of non-combustible material and have a high fire resistance.	Concrete as a material is inert and non-combustible (class A1). Most of its strength is retained in a typical fire due its low thermal conductivity.
3. To limit the generation and spread of fire and smoke.	Walls and ceilings should be made of non-combustible material; fire separating walls should be non-combustible and have a high fire resistance.	In addition to the above statements adequately designed connections using concrete are less vulnerable to fire and make full use of structural continuity.
4. To assist the evacuation of occupants and ensure the safety of rescue teams.	Escape routes should be made of non-combustible material and have a high fire resistance, which can be used without danger for a longer period.	Concrete cores are extremely robust and can provide very high levels of resistance.
5. To facilitate the intervention of rescue parties (firefighters).	Loadbearing elements should have a high fire resistance to enable effective firefighting; there should be no burning droplets.	In addition to all of the above statements, in most fires, concrete will not produce any molten material.

Experience of fires

Lessons can be learnt from the performance of buildings in real fires. A large number and variety of fire damaged concrete structures in the UK have been investigated [1]. Part of the investigation collected information on the performance, assessment and repair of over 100 structures including dwellings, offices, warehouses, factories and car parks of both single and multi-storey construction. The forms of construction examined included flat, trough and waffle floors, plus associated beams and columns, and examples of in-situ and precast concrete construction in both reinforced and prestressed concrete.

Examination of this information showed that:

- Most of the structures were repaired. Of those that were not, many could have been repaired but were instead demolished for reasons other than the damage sustained.
- Almost without exception, the structures performed well during and after the fire.

Case study

The Windsor Tower, Madrid, Spain (2005)

The protection provided by concrete is clearly shown by the behaviour of the Windsor Tower, Madrid during a catastrophic fire in February 2005. The concrete column and cores prevented the 29-storey building from total collapse, while the strong concrete transfer beams above the 16th floor contained the fire above that level for seven hours.

The fire caused €122 million of damage during the refurbishment of a major multi-storey office building in Madrid's financial district and provides an excellent example of how traditional concrete frames perform in fire.

Built between 1974 and 1978, the Windsor Tower included 29 office storeys, five basement levels and two 'technical floors' above the 3rd and 16th floors. The 'technical' or strong floors, each with eight super-deep concrete beams (measuring 3.75m in depth; the floor to ceiling height elsewhere), were designed to act as massive transfer beams. The shape of the building was essentially rectangular, measuring 40m x 26m from the third floor and above. Normal strength concrete was used for the structural frame's central internal core, columns and waffle slab floors with the floors also supported by tubular steel column props on the facade.

The concrete structure remained intact, except above the technical floor at level 16, where the steel perimeter columns failed and as a result the slab they supported collapsed.

At the time of the structure's original design, water sprinklers were not required in Spanish building codes. With subsequent amendments to legislation, the tower was being refurbished to bring it into line with current regulations. The scope of the refurbishment work included fireproofing every steel perimeter column, adding a new facade and external escape stairs, and upgrading alarm and detection systems, as well as the addition of two further storeys.

The fire broke out late at night on the 21st floor, almost two years after the start of the refurbishment programme, and at a time when the building was unoccupied. Once started, the fire spread quickly upwards through openings made during the refurbishment between perimeter columns and the steel/glass facade. It also spread downwards as burning facade debris entered windows below. The height, extent and intensity of the blaze meant firefighters could only try to contain it and protect adjacent properties while the fire raged for 26 hours, engulfing almost all the floors in the building.

When the fire was finally extinguished, the building was completely burnt out above the fifth floor. With most of the facade destroyed, there were fears that the tower would collapse. However, throughout the fire and until eventual demolition, the structure remained standing. Only the facade and floors above the upper concrete 'technical floor' suffered collapse.

The perimeter steel columns above the upper technical floor had yet to be fire-proofed during the refurbishment works. These failed and the slabs which they supported collapsed. Some internal concrete columns also subsequently failed due to increased loading from slabs that had lost their perimeter support or the impact of falling slabs. The passive resistance of the concrete columns and core helped prevent total collapse, but the role of the two concrete 'technical floors' was critical, particularly the one above the 16th storey, which contained the fire for more than seven hours. It was only then, after a major collapse, that falling debris caused fire to spread to the floors 15 and below. But even then, damage was limited to the storeys above the lower 'technical floor' at the third level.

This presents powerful evidence of the inherent passive fire resistance of concrete and also that strong concrete floors placed at regular intervals in a structure can minimise the risk of progressive collapse and prevent the spread of fire. The forensic report on the fire performance of the Windsor Tower was carried out by Spanish researchers from the Instituto Tecnico de Materiales y Constucciones (Intemac). The independent investigation focused on the fire resistance and residual bearing capacity of the structure after the fire. Amongst Intemac's findings, the report states that:

"The Windsor Tower concrete structure performed extraordinarily well in a severe fire."

"The need for due fireproofing of the steel members to guarantee their performance in the event of a fire was reconfirmed. Given the performance of these members on the storeys that had been fireproofed, it is highly plausible, although it can obviously not be asserted with absolute certainty, that if the fire had broken out after the structure on the upper storeys had been fireproofed, they would not have collapsed and the accident would very likely [have] wreaked substantially less destruction".

Continuous improvement

The role of research and development

During a fire, concrete performs well, both in terms of its material properties and as a structural element. However, driven by a culture of continual improvement, the concrete industry continues to undertake research into the inherent characteristics of the material that allow it to perform well in the event of fire.

Systematic research into the effects of fire on concrete buildings dates back to the early 1900s, when researchers began looking into both the behaviour of concrete as a material and the integrity of concrete structures. François Hennebique, one of the pioneers of reinforced concrete, carried out a full scale test in Paris as early as 1920 at a firefighter's congress. From 1936 to 1946 a series of tests was carried out at the Fire Research Station in Borehamwood, in the UK. These tests formed the basis of modern design codes for concrete structures such as CP 110, the code which later became BS 8110. Further information on major changes to fire design codes in the UK can be found in the comprehensive Building Research Establishment (BRE) study *Fire safety of concrete structures: Background to BS 8110 fire design* [4]. This report explains how research and development has informed code development and how newer, performance-based approaches are better equipped to facilitate the efficient design of robust concrete structures.

A full scale fire test was carried out on an in-situ flat slab in the concrete test building at BRE Cardington in September 2001. The building was designed as part of a research project into the process of construction, for which the fire test was not a primary objective. The high-strength concrete with high moisture levels was therefore not typical of buildings and designers would have taken additional efforts to minimise spalling if it was a real building. As a result, extensive spalling occurred, but despite this, the slabs supported the loads throughout the test and afterwards. The results from the test were summarised in the BRE publication *Constructing the Future* issue 16 as "The test demonstrated excellent performance by a building designed to the limits of Eurocode 2". The report stated "The building satisfied the performance criteria of load bearing, insulation and integrity when subjected to a natural fire and imposed loads. The floor has continued to support the loads without any post fire remedial action being carried out." [5]

Two full scale tests were carried out in March 2006 on precast hollowcore floors supported on fire protected steel frames at the BRE fire test facility at Middlesbrough. Each fire test was carried out on a three-bay frame with 200mm deep hollowcore units, without any structural topping, spanning seven metres resulting in a total floor plate area of 125m^2. The two tests were identical with the exception of the second test having a more robust detail to tie the units and the supporting steel beams together. Both floor plates which were subjected to very severe fire conditions performed extremely well supporting the imposed loads during both the heating and cooling phases of the fire. The results of the tests demonstrated that a beneficial load path was created by lateral thermal restraint to the floor units and that full scale testing replicated the experience gained from real fires where precast hollowcore floor slabs have been proven to have excellent overall inherent fire resistance [6].

Moving from prescriptive to performance-based design

One of the most significant changes in fire safety design for structures has been the move away from prescriptive, tabulated code values for individual elements, which are based on research tests and observations of fire-affected structures. Such data can be inherently conservative when translated into generic tables because it assumes that elements act in isolation and are fully stressed, whereas the elements in any structure act quite differently – as part of a whole.

Individual elements that conform to a particular rating (as tested on a specimen in a 'standard' fire) normally have a better fire performance when acting as part of a structure. In fact, the use of prescriptive, target fire resistance ratings such as those found in BS 8110 has been found to be rather limiting in practice, particularly in fire engineered structures. Elements are classified in strict time periods (e.g. 30, 60, 90 or 120 minutes). The delineation between aggregates is based simply on lightweight or dense concrete, which does not reflect the range of concretes commonly used today.

For these reasons, performance-based structural analysis has come to the fore. Computer modelling techniques are now capable of simulating structural conditions that are very difficult to study even in a full-scale fire test. The development of such software has encompassed thermal analysis (for separating walls), structural analysis (for loadbearing floors) and hydral analysis (to predict moisture movement and spalling). Computer programs capable of performing all three types of analysis (thermohydromechanical analysis) were first developed in the 1970s. They have been refined by European researchers in the UK and Italy, particularly in response to tunnel fires and several 3D software tools have been developed for advanced analysis of complex structures.

Since the 1990s, the performance-based approach has permeated into national building codes in countries such as Sweden, Norway, Australia and New Zealand, allowing a cost effective and highly adaptable approach to design. Eurocode 2 is based on such an approach to fire safety design. By considering minimum dimensions in terms of load ratios for individual elements, Eurocode 2 is inherently more flexible and well founded in its methodology.

Almost **100 years of dedicated research** into concrete's inherent strengths in fire has resulted in a culture of continuous improvement.

Use of fibres to prevent spalling

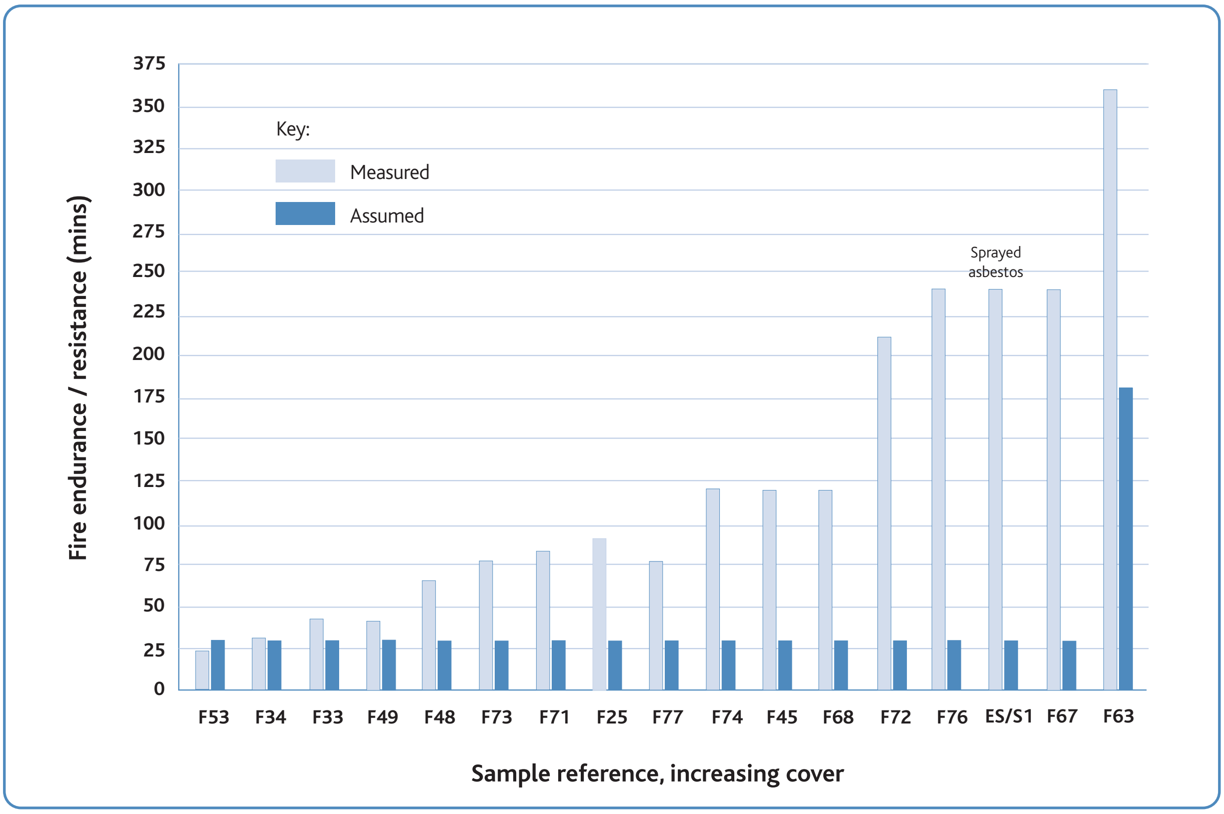
Spalling may sometimes be a part of concrete's response to the high temperatures experienced in a fire. For normal buildings and normal fires (e.g. offices, schools, hospitals, residential), design codes already include the effect of spalling for these applications. For example, research on the experimental results used as the basis for developing the UK structural concrete design code (BS 8110) found that these results supported the assumed periods of fire resistance and in many cases were very conservative (Lennon, 2004).

Figure 3 shows a comparison between floor slab performance in fire tests and their assumed performance within BS 8110. Many of the specimens experienced spalling during the fire tests, so the fact that most slabs exceed assumed levels of performance is clear evidence that spalling is accounted for in design codes.

High performance concretes, which are often used for tunnels and bridges, can be particularly vulnerable to spalling because these specifications are very dense. High performance concretes are characterised by low permeability, which can mean that pore pressure can easily build up. One option is to cover the surface of the structural concrete with a thermal barrier. However, a more efficient solution is to incorporate polypropylene fibres within the concrete mix. Researchers believe that by melting at 160°C, these fibres and any micro cracks adjacent to them provide channels for moisture movement within the concrete, thus increasing permeability and reducing the risk of spalling.

The use of fibres in high performance concrete is a proven technique. Research is continuing to optimise performance.

Figure 3: Comparison between measured (light blue) and assumed (dark blue) fire resistance based on depth of cover (from Lennon 2004)



Concrete in extreme applications

Performance in fire

Concrete is versatile and adaptable, and the structures it creates can be designed to give protection from fire in even the most extreme fire conditions.

Tunnels

Tunnel fires can reach very high temperatures, particularly when burning fuel, asphalt and vehicles are part of the incident. Temperatures have reportedly reached up to 1,350°C, but more usually reach around 1,000 - 1,200°C. Peak temperatures in a tunnel fire are reached more quickly than in buildings mainly because of the calorific potential of hydrocarbons contained in petrol and diesel fuel.

Major incidents, such as the fires in the Channel Tunnel (1996), Mont Blanc Tunnel (1999) and St Gotthard Tunnel (2001), have publicised the devastating consequences of tunnel fires.

The use of concrete for road surfaces in tunnels is helpful. It can provide part of the structural design of the tunnel and just as important, because concrete does not burn, it does not add to the fire load within the tunnel. ***Since 2001, all new road tunnels in Austria over one kilometre in length have been required to use a concrete pavement.***

Tunnel fires can reach extremely high temperatures, therefore concrete is a good choice for tunnel linings. Courtesy of Tarmac.

Concrete is often used as a tunnel lining on its own or with a thermal barrier. Much research has gone into developing concrete lining materials to minimise the effects of spalling from lining surfaces when exposed to severe fires.

Protective structures

Concrete is probably the most versatile material in the world with which to build protective structures for defence, research or commercial purposes. It can be moulded into almost any shape and designed to withstand predicted imposed dynamic or static stress. Where radiation shields are necessary, normal weight concrete is considered to be an excellent material for construction because it attenuates both gamma and neutron radiation. Concrete is used in pressure and containment vessels for nuclear reactors and for particle accelerators such as cyclotrons. The addition of heavier aggregates such as haematite makes concrete even more effective at preventing gamma ray penetration. This performance characteristic of concrete applies not only to protective shields but also to the storage of radioactive waste and structures in which isotopes are handled.

Blast protection

Structures that are specifically meant to afford protection against blasts include missile silos, explosive stores, facilities where explosives are handled and tested, factories where explosive conditions can arise, and military and civil defence shelters. Concrete is well suited for such structures, whether for underground use or located within a normal building.

In addition, there is growing awareness of the vulnerability of buildings to external attack. The UK Secure and Sustainable Buildings Bill is likely to propose changes to building design to improve blast protection, particularly for Government properties. Precast concrete cladding panels used on the MI6 Headquarters in London prevented the building suffering significant damage after a rocket attack in September 2000.

Liquid fuel storage

Concrete storage tanks for oil and other flammable liquids can be seen all over the world. Due to concrete's excellent fire resistance compared with some other materials, concrete liquid fuel storage tanks can be built nearer to one another with the reassurance that a fire local to one tank is less likely to spread to adjacent tanks.

The excellent fire protecting qualities of concrete mean that it does not have to rely on any additional active or passive measures.

Lessons from around the world

Building regulations and construction details vary in different countries but generic lessons can be learnt from overseas.

Independent fire damage assessment

An independent investigation of the cost of fire damage in relation to the building material which houses are constructed from was based on statistics from the insurance association in Sweden (Forsakringsforbundet). The study was on large fires in multi-family buildings in which the value of the structure insured exceeded €150k. The sample set was 125 fires which occurred between 1995 and 2004. The results showed that:

- The average insurance payout per fire and per apartment in concrete/masonry houses is around one fifth that of fires built from other materials (approx €10,000 compared with €50,000)

- A major fire is less than one tenth as likely to develop in a concrete/masonry house than one built in other materials

- Of the concrete houses that burned only nine per cent needed to be demolished whereas 50 per cent of houses built from other materials had to be demolished.

Lower insurance premiums with concrete

Every fire causes an economic loss. In most cases, insurers have to pay for the damage caused. For this reason, insurance companies maintain comprehensive and accurate databases on the performance of all construction materials in fire. This knowledge is often reflected in reduced insurance premiums.

Insurance premiums for concrete buildings across mainland Europe tend to be less than for buildings constructed from other materials which are more often affected badly or even destroyed by fire. In most cases, concrete buildings are classified in the most favourable category for fire insurance due to their proven fire protection and resistance. Of course, every insurance company will have its own individual prescriptions and premium lists, which will differ between countries. The fact remains, however, that because of concrete's good performance, most insurers will offer benefits to the owners of concrete buildings. When calculating a policy premium, insurers will take the following factors into account:

- Material of construction
- Type of roof material
- Type of activity/building use
- Distance to neighbouring buildings
- Nature of construction elements
- Type of heating system
- Electric installation(s)
- Protection and anticipation (preparedness)

For example, insurance premiums for warehouses in France are reduced if concrete is chosen [7]. Selecting a concrete frame and walls for a single storey warehouse presents a possible 20 per cent reduction on the 'standard'/average premium paid. In deciding the final premium, the insurers also take into account security equipment, fire prevention and suppression measures, which include compartmentation – a fire prevention option which concrete construction options excel at.

In many cases concrete structural frames **will exceed performance expectations in the event of a fire.**

Summary

Fire safety is a key consideration in the design and use of buildings and structures. Extensive legislation and design codes are in place to protect people and property from the hazards of fire. The continuous development of these codes has ensured that ongoing research and development work is incorporated in current practices during design, construction and occupancy.

Extensive research into the performance of concrete in fire means that there is an excellent understanding of the behaviour of concrete both in a structure and as a material in its own right. This basic science will provide the essential information to support the move from prescribed tabulated values for fire resistance to computer simulation and performance-based fire safety engineering.

While prescriptive data will continue to have a role to play, new standards such as Eurocode 2 incorporate greater degrees of flexibility on the sizing of concrete elements for fire safety. This means designers will have scope for more efficient design of concrete structures that meet everyone's needs.

Eurocode 2 also provides a mechanism for designers to provide a level of protection in excess of regulations. Clients may choose this so as to increase property safety rather than only provide minimum life safety protection.

Benefits of using concrete:

- Concrete does not burn, and does not add to the fire load
- Concrete has high resistance to fire, and stops fire spreading
- Concrete is an effective fire shield, providing safe means of escape for occupants and protection for firefighters
- Concrete does not produce any smoke or toxic gases, so helps reduce the risk to occupants
- Concrete does not drip molten particles, which can spread the fire
- Concrete restricts fire, reducing the risk of environmental pollution
- Concrete provides built-in fire protection – there is normally no need for additional measures
- Concrete can resist extreme fire conditions, making it ideal for storage premises with a high fire load
- Concrete's robustness in fire facilitates firefighting and reduces the risk of structural collapse
- Concrete is easy to repair after a fire, and so helps businesses to recover sooner
- Concrete is not affected by the water used to quench a fire
- Concrete pavements stand up to the extreme fire conditions encountered in tunnels

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Acknowledgements

The Concrete Centre wishes to acknowledge assistance from BCA and CEMBUREAU in the preparation of this document.

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Ref: **TCC/03/43**
ISBN: **978-1-904818-64-9**
First published 2008

www.concretecentre.com