



The **Concrete** Centre™

Concrete and Fire

USING CONCRETE TO ACHIEVE SAFE, EFFICIENT
BUILDINGS AND STRUCTURES



CONTENTS

- 1 Introduction
- 2 Protecting people and property:
the role of fire safety standards
- 4 What happens to concrete in a fire
- 6 Material and structural performance
- 8 Putting it all together: fire engineering
- 10 Continuous improvement: the role
of research and development
- 12 Summary
- 13 Further reading

Fire test on concrete frame at BRE.



Front cover, main image:
The Royal College of Obstetricians and Gynaecologists, Regents Park
Architects: Nicholas Hare Architects LLP
Photographer: Martin Charles

INTRODUCTION

In fire, concrete performs well as an engineered structure and as a material in its own right: this publication explains how.

It is vitally important that we create buildings and structures that protect both people and property as effectively and as efficiently as possible. Annual statistics on deaths caused by fires in the home and elsewhere make for unpleasant reading and sadly it is often through these events that we learn more about fire safety design.

A mass of national and international legislation exists to protect us from the hazards of fire and it is being updated continuously as a result of research and development. However, this can prove unwieldy for all but technical fire specialists – straightforward information and guidance is required for busy professionals, whether they be architects, specifiers, insurers or from Government bodies. This publication is aimed at precisely these people who need a summary of the importance of fire safety design and the role which concrete can play in preventing the spread of fire and protecting lives. Buildings and structures are covered and reference is made to tunnels and other more extreme situations where concrete is used.

Concrete is specified in building and civil engineering projects for several reasons, sometimes cost, sometimes speed of construction or architectural appearance, but one of concrete's major inherent benefits is its performance in fire, which may be overlooked in the race to consider all the factors affecting design decisions.

In most cases, concrete does not require any additional protection because of its built-in resistance to fire. It is non-combustible (i.e. it does not burn) and has a slow rate of heat transfer, which makes it a highly effective barrier to the spread of fire. Design of concrete structures for fire is related to the strength, continuity of reinforcement and adequate detailing of connections.

Ongoing research has included work on fibre reinforcement and is supporting the move from prescriptive design codes to a performance based approach founded on calculation methods and advanced computer models. These demonstrate how concrete structures can be designed robustly for the most severe fire conditions.

Readers should note that this is not a comprehensive guide on fire safety design; rather it is an overview of the key issues as they relate to concrete. A list of relevant codes and standards is given on page 13 for those seeking further technical information.



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

PROTECTING PEOPLE AND PROPERTY: THE ROLE OF FIRE SAFETY STANDARDS

We are all aware of the damage that fire can cause in terms of loss of life, homes and livelihoods and it is always disturbing to hear of such events.

A study of 16 industrialised nations (13 in Europe plus the USA, Canada and Japan) found that, in a typical year, the number of people killed by fires was 1 to 2 per 100,000 inhabitants and the total cost of fire damage amounted to 0.2% to 0.3% of GNP. In the USA specifically, 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 and these 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 extent of such damage will depend on a number of factors such as building design and use, structural performance, fire extinguishing devices and evacuation procedures. This is by no means an exhaustive list, but it shows how fire safety is a formidable subject and requires clear and effective legislation, and codes and guidance on design, construction and occupancy. 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 crucial in ensuring fire safe construction.

Codes and regulations on fire safety are updated continually, usually as a result of research and development. However, rather more dramatic revisions may take place in response to disasters or catastrophic events, which can require immediate and/or significant actions to prevent reoccurrence. This dates back as far as the Great Fire of London in 1666 when fire swept through the streets of overcrowded, timber framed housing causing death and devastation. This resulted in fundamental changes to patterns of development in the city thereafter. In fact, this is when the orientation of the floors, joists and beams was changed from running parallel to a row of terraced houses (and so providing a continuous wooden connection between adjacent houses), to running from front to back.

More recently, research following the World Trade Centre disaster in 2001 is resulting in revisions to fire safety aspects of building codes relating to tall buildings, and in particular the need for robust design. Progress in structural design and materials technology has made structures easier to construct, more durable and more efficient in the use of materials. The question remains whether structures should also be designed to survive extreme events. Concrete is very durable under most conditions and, with correct design and detailing, can make a vital contribution to a building's inherent robustness.



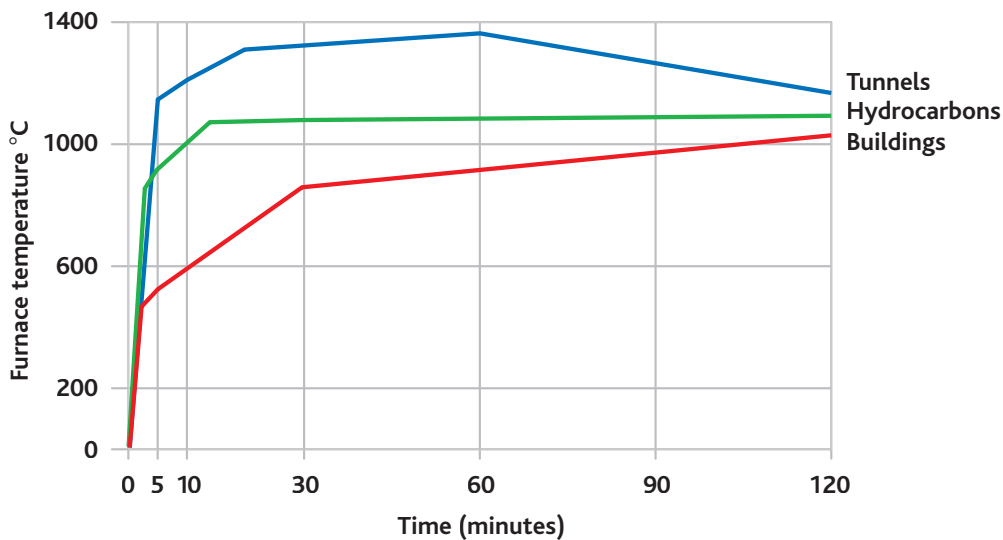
The Pentagon Building performance report, produced as part of this research, states that the structural resilience imparted by the design and construction of this concrete building provided resistance to progressive collapse. It also states that it is important to integrate such features as continuity, redundancy, energy absorbing capacity and reserve strength, which is vital for high occupancy buildings.

In practice, standard testing methods are used to determine the fire performance of materials and building or structural elements. These replicate the conditions of typical fires, either on a smaller scale (e.g. in a specially built oven/furnace) or in a full-scale test (i.e. on a part or whole mock-up of a building).

Strict controls on the temperatures and rate of rise in temperature are published for three specific scenarios, based on the conditions experienced in real fires.

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



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

EXPERIENCE OF FIRES

The Concrete Society investigated a large number and variety of fire damaged concrete structures within the UK. Part of this investigation detailed information gathered 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, and associated beams and columns, of in-situ and precast construction and both reinforced and prestressed concrete.

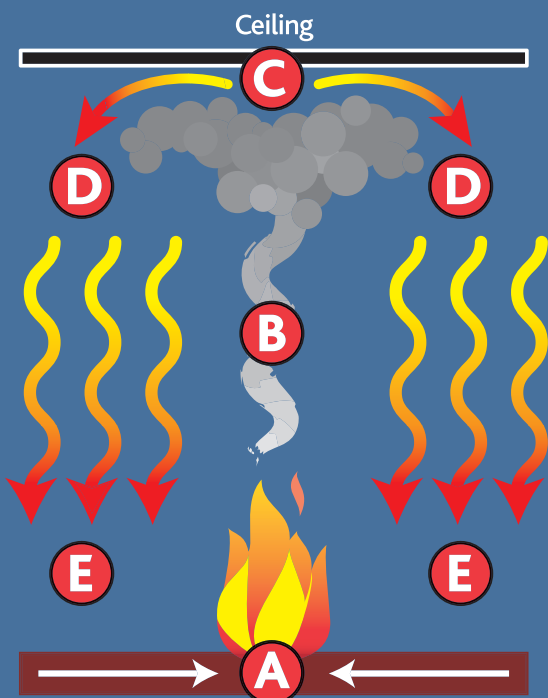
Examination of the items for damage and repair showed that:

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



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.

Diagrammatic representation of standard compartment fire.



WHAT HAPPENS TO CONCRETE IN A FIRE

FIRES

Fires require three components:

- Fuel
- Oxygen
- Heat source

Fires are caused by accident, energy sources or natural means, but the majority of fires in buildings are caused by human error (e.g. discarded cigarettes). Once a fire starts and the contents and/or materials in a building are burning, then the fire spreads via radiation, convection or conduction with flames reaching temperatures of between 600°C and 1200°C. Harm 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' like 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.

For these reasons concrete is said to have a high degree of fire resistance and, in the majority of applications, concrete can be described as virtually 'fireproof'. This excellent performance is due in the main to concrete's constituent materials (i.e. cement and aggregates) which, when chemically combined within concrete, form a material that is essentially inert and, importantly for fire safety design, has a relatively poor thermal conductivity. It is this slow rate of heat transfer (conductivity) 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 and so internal zones do not reach the same high temperatures as a surface exposed to flames. A standard ISO 834/BS 476 fire test on 160 mm wide x 300 mm deep concrete beams has shown that, after one hour of exposure on three sides, while a temperature of 600°C is reached at 16 mm from the surface, this value halves to just 300°C at 42 mm from the surface – a temperature gradient of 300 degrees in about an inch of concrete!

Even after a prolonged period, the internal temperature of concrete remains relatively low; this enables it to retain structural capacity and fire shielding properties as a separating element.

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

When concrete is exposed to the high temperatures of a fire, a number of physical and chemical changes can take place. These changes are shown in the chart below, which relates temperature levels within the concrete (not the flame temperatures) to some indicative changes in its properties.

CONCRETE IN FIRE: PHYSIOCHEMICAL PROCESSES

Temperature (°C)	What happens
1000	
900	Air temperatures in fires rarely exceed this level, but flame temperatures can rise to 1200°C and beyond.
800	
700	
600	Above this temperature, concrete is not functioning at its full structural capacity.
550-600	Cement-based materials experience considerable creep and lose their loadbearing capacity.
400	
300	Strength loss starts, but in reality only the first few centimetres of concrete exposed to a fire will get any hotter than this, and 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

Inspection of fire-affected structures is based on a visual check and comparison with similar cases. Any concrete exposed to temperatures above 300°C is removed and replaced. Below this temperature, concrete can be repaired by increasing the overall dimensions to take the design load. Often all that is required is a simple clean up. Speed of repair is an important factor in minimising the loss of business after a major fire.

Repair is preferable to demolition and reinstatement for cost reasons. The Concrete Society's report *Assessment and repair of fire damaged concrete structures** gives a comprehensive account of this issue.

In reality, the behaviour of concrete in fire can be rather complex and will very much depend on a number of factors including mix design, imposed loads and structural design, which are outlined in the next section.

* See page 13

Concrete provides protection against heat from fire.



Dousing a fire test at BRE.



Concrete is a non-combustible material. It can also be used effectively as a loadbearing, separating and fire-shielding structural element – in a single operation.

MATERIAL AND STRUCTURAL PERFORMANCE IN FIRE

There are two key components to concrete's successful performance in fire; first its basic properties as a building material and secondly, its functionality in a structure. We know that concrete is non-combustible and that it has a slow rate of heat transfer. These benefits applied via appropriate mix design and adequate structural detailing mean that, in the vast majority of structures, concrete can be used without any additional fire protection.

CONCRETE AS A MATERIAL

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) and in 1996 the European Commission compiled a binding list of approved materials for this classification, which 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 fire).

CONCRETE IN STRUCTURES

For concrete structures in general, good design for fire safety means creating a robust structure with adequate continuity of reinforcement and alternative load paths. But how does this overall aim translate to individual elements? Codes such as BS 8110 and Eurocode 2 are based on the premise that such elements require a measure of fire resistance appropriate to their location, function, load, level of reinforcement and, of course, size and shape.

Fire resistance is the ability of a particular structural element (rather than a generic building material) to fulfil its designed function for a period of time in the event of a fire. The function will depend on the element's position and role within the structure, i.e. whether it has any fire protecting/separation role, and the time component relates to the time elapsed before one of three fire limit states below is breached; these appear in UK and European fire safety codes.



Fire Limit States

- A: The structure should retain its loadbearing capacity.
- B: The structure should protect people from harmful smoke and gases.
- C: The structure should shield people from heat.

Tabulated values from BS 8110.

Dense, simply supported, solid reinforced concrete slab:

Fire resistance period	30 minutes	60 minutes	90 minutes	120 minutes	180 minutes	240 minutes
Thickness (mm)	75	95	110	125	150	170
Cover (mm)	15	20	25	35	45	55

Lightweight, simply supported, solid reinforced concrete slab:

Fire resistance period	30 minutes	60 minutes	90 minutes	120 minutes	180 minutes	240 minutes
Thickness (mm)	70	90	105	115	135	150
Cover (mm)	15	15	20	25	35	45

Dense, concrete column: fully exposed

Fire resistance period	30 minutes	60 minutes	90 minutes	120 minutes	180 minutes	240 minutes
Thickness (mm)	150	200	250	300	400	450
Cover (mm)	20	25	30	35	35	35

Lightweight concrete column: fully exposed

Fire resistance period	30 minutes	60 minutes	90 minutes	120 minutes	180 minutes	240 minutes
Thickness (mm)	150	160	200	240	320	360
Cover (mm)	20	20	25	35	35	35

The heat flow generated by fire in concrete structures 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 changes 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 measurements to consider:

1. Overall dimensions, such that the temperature of the concrete throughout the section does not reach critical levels.
2. Average concrete cover, such that the temperature of the reinforcement does not reach critical levels (500°C for steel reinforcing 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 have been compiled, which have on the whole been extremely useful because of their inherent simplicity. An indicative set of minimum dimensions is shown on page 6 for both dense concrete and lightweight concrete elements. Readers should refer to BS 8110 for a comprehensive set of data tables.

It is important to note that Eurocode 2 adopts a different approach to fire safety design, which is much more flexible than prescriptive data tables. It is based on the concept of 'load ratio', which is the relation of the load applied at the fire limit state to the capacity of the element at ambient temperature.

Readers should refer to the Eurocode documentation for further details. See www.eurocode2.info for information.

NEW FIRE STUDY

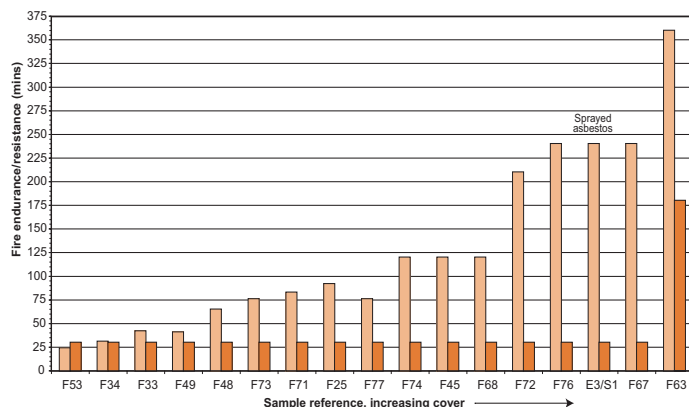
A recent report has been prepared at the request of The Concrete Centre and the British Cement Association to investigate the background to the methods for establishing the fire resistance of concrete structures specified in the relevant parts of the UK concrete Code BS 8110. The work focused on the original research and test results underpinning the tabulated data in BS 8110, which have been revisited in order to assess the relevance of the approach to modern forms of concrete construction.

This study is important in that it brings together in one document a body of information covering test

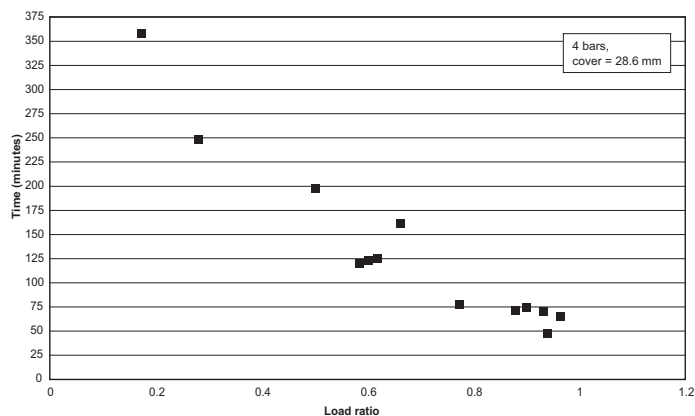
results and research carried out over a number of years. There was a danger that much of the important work in support of the development of codes and standards would be lost. Hence a study was carried out to collate and assess all relevant information to ensure that the important lessons from the past are recorded and to help define the strategy for a new generation of codes and standards.

The investigation showed that the experimental results used as the basis for developing the tabulated data in BS 8110 support 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.

The figures below are taken from the new fire report. The first is a comparison between the performance from fire tests and the assumed performance from the Code for restrained floor slabs, based purely on the depth of cover. The requirements are based on the failure of those specimens where spalling took place. Spalling has therefore been taken into account in the development of tabulated data.



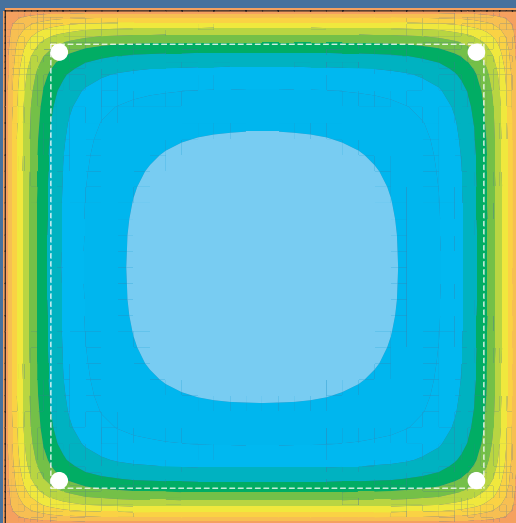
Comparison between measured (buff) and assumed (orange) periods of fire resistance based on depth of cover.



Relationship between applied load ratio and fire resistance for reinforced concrete columns.

The excellent fire protecting qualities of concrete place it firmly ahead of competitors when it comes to fire engineering.

Diagram of temperature gradients within a column at time of maximum air temperature during a fire (from BRE report).



---- An approximation of the 500°C isotherm as used during a design check.

● Reinforcing steel

PUTTING IT ALL TOGETHER: FIRE ENGINEERING

Moving on from the physical characteristics of concrete as a material and its performance in fire it is important to place this information in the context of whole building design. For any building or structure, regardless of its complexity, design for fire safety should address the following:

- Passive measures: these contain the fire and prevent structural collapse, e.g. fire resisting floors and walls.
- Active measures: these control the fire itself and/or facilitate the evacuation of occupants, e.g. automatic fire alarms, sprinkler systems, smoke control fans and smoke vents.

Passive measures are the mainstay of fire safety design; inherently fire-resistant materials such as concrete are vital. An over-reliance on active measures such as sprinklers is not advisable – water supplies may be subject to even greater demand in the future and may not always be available.

Good practice in design for fire safety incorporates these aspects and more in what is termed 'fire engineering' for large, complex structures that warrant additional design effort. This approach is based on first principles and thus develops a specific solution for a specific design, which aims to be the most efficient and effective.

Although prescribed data (such as dimensions for thickness and cover) may be used, the aim of fire engineered structures is to move away from the traditional methods and create a fire strategy dedicated to the project in hand, based for example on the building's design, how it will be used, fuel load and the probability of a fire occurring. For this reason, computer software is used to perform the probabilistic analysis of the behaviour of both fire and people.

Fire engineering considers the problem of fire safety in a holistic way, giving due attention to issues such as property protection where appropriate. An emphasis on first principles means that the final structure can be designed as efficiently as possible because all factors relating to fire safety have been taken into consideration at an early stage in the design process. This upfront approach ensures that undue pressure is not put upon the structural engineer to 'design in' additional fire protection at the last moment, which can be a costly and time consuming business.

Taking a responsible, realistic approach to fire engineering calculations is critical. The design of structures should not only meet requirements, but exceed these to allow for the 'panic' factor – people leaving buildings in an emergency do not necessarily behave according to the strict logic of a fire engineering calculation.

Good decision making early on in the procurement and design process can make all the difference and concrete is an excellent choice due to its inherent fire resistance properties, which can be further refined in detailed design. Concrete is also extremely compatible with a fire engineering approach because the full effect of its structural continuity can be utilised, potentially making it structurally much more efficient.

From a whole building standpoint, concrete can satisfy the four principal objectives of fire safety in a number of ways – some examples are given opposite relating to recent European legislative requirements.

CONCRETE IN EXTREME APPLICATIONS

Concrete is the most important construction material used today. Vast volumes of it have been and are still being used to build structures, many of which are erected to protect life, the environment and property. Concrete is versatile and adaptable, and the structures it creates can be designed to afford the desired protection.

Objective	Requirement	Use of concrete
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.
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, adequately designed connections using concrete are less vulnerable to fire and make full use of its structural continuity.
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. Slipforming or jumpforming are particularly effective methods of construction.
To facilitate the intervention of rescue parties (fire fighters)	Loadbearing elements should have a high fire resistance to enable effective fire fighting; there should be no burning droplets.	In addition to the above statements, in most fires, concrete will not produce any molten material.

Tunnels

Tunnel fires tend to reach very high temperatures due to burning fuel and vehicles, reportedly up to 1350°C, but usually around 1000 - 1200°C. Peak temperatures 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 those in the Channel Tunnel (1996), Mont Blanc (1999) and St Gotthard (2001), have publicised the devastating consequences of tunnel fires and the various shortcomings of the construction materials and structural solutions involved.

The use of concrete for road surfaces in tunnels is helpful, not only because it can provide part of the structural design, but also because it does not burn and therefore does not add to the fire load within the tunnel. **From 2001, all new road tunnels in Austria over one kilometre in length were required to use a concrete pavement.** Concrete is often used as a tunnel lining on its own or with a thermal barrier. Much research effort has gone into developing these lining materials to minimise the effects of spalling from concrete 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 the strength necessary 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 gamma and neutron radiation. Concrete is used, for example, 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 the building material of choice for such structures, whether for an underground structure or one 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 MI5 Headquarters in London prevented the building suffering significant damage after a rocket attack a few years ago.

Liquid fuel storage

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

Copyright: Daylight.com



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

CONTINUOUS IMPROVEMENT: THE ROLE OF RESEARCH AND DEVELOPMENT

We know that concrete fares well in fire both as a material and as a structural element, but what can be done to improve its performance even further? There are three main aspects of concrete's behaviour in fire that have warranted specific research and development, to improve:

1. Understanding of the physical and chemical changes that occur.
2. Predicting the effects of these changes.
3. Proposing strategies to prevent any deterioration that could compromise structural integrity (loss of strength) and/or fire resistance (loss of protection via spalling).

Systematic research into the effects of fire on concrete buildings dates back to the early 1900s, with scientists looking at 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 firefighters congress. From 1936 to 1946 a series of tests was carried out at the Fire Research Station in Borehamwood; these formed the basis for modern design codes for concrete structures such as CP 110, which later became BS 8110. Further information on the major changes to fire design codes in the UK is covered in the comprehensive BRE study *Fire safety of concrete structures: Background to BS 8110 fire design**. 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 the concrete test building at BRE Cardington in September 2001. The results from the test were summarised in the BRE publication *Constructing the Future* issue 16. The article said, "The test demonstrated excellent performance by a building designed to the limits of Eurocode 2". The report also went on to state, "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."

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 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 we know that the elements in concrete structures 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) can be expected to have a much 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) and 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 (using computers) has come to the fore with modelling techniques now capable of simulating structural conditions that are very difficult to study even in a full-scale fire test, such as cooling patterns after collapse. The development of such software has encompassed thermal analysis

* See page 13



(e.g. for separating walls), structural analysis (e.g. for loadbearing floors) and hydral analysis (i.e. to predict moisture movement and spalling). Computer programs capable of performing all three types of analysis (thermohydromechanical analysis) were first developed in the 1970s and have been refined by European researchers in the UK and Italy, particularly in response to tunnel fires.

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

USE OF FIBRES TO PREVENT SPALLING

Research has also focused on the use of fibres in concrete as a means of preventing the worst cases of spalling (where pieces of concrete fall away from the surface of a structural element when it is exposed to high temperatures). It is caused mainly by a build up of pressure beneath the concrete surface (in pores) so cracks develop parallel to the surface. When the sum of such stresses exceed that which the concrete can accommodate, there is a sudden release of energy and a portion of the heated area breaks away.

The worst examples can occur, for example, in tunnel fires, where burning vehicles, fuel and loads have caused major incidents. Here the concrete tunnel lining may reach a very high temperature and concrete particles may spall, sometimes explosively, away from the surface.

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

The use of fibres is a proven technique and research is continuing to optimise performance. Computer software is now available that predicts spalling by modelling the build up of pore pressures in concrete during fire. These models give a far more accurate picture of what is a very complex phenomenon, enabling designers to produce more efficient concrete structures.

Polypropylene fibres provide protection against spalling.



Concrete is a versatile material and when appropriately designed is inherently fire proof due to its non flammability and thermal insulation properties.

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 on the performance of concrete in fire means that we have 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 engineering.

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

BENEFITS OF USING CONCRETE

- Concrete is non-combustible (i.e. it does not burn).
- Concrete is inherently fire resistant (i.e. it does not support the spread of fire).
- Concrete has a slow rate of heat transfer (making it an effective fire shield).
- Concrete does not produce any smoke, toxic gases or emissions in a fire situation.
- Concrete does not contribute to the fire load of a building.
- Under typical fire conditions, concrete retains most of its strength.
- Polypropylene fibres can be used to prevent spalling.
- Skillful mix design further refines concrete's inherent performance.
- For the vast majority of applications, concrete does not require any additional, costly fireproofing measures.
- Fire damage to concrete is typically minimal, requiring only a minor clean up.
- Concrete has been given the highest possible material classification for its fire resistance.
- Connections designed using concrete are more robust in a fire situation.
- Bespoke concrete mixes can be designed to cater for extreme fire loads.



FURTHER READING

- Building Research Establishment. *Fire safety of concrete structures: background to BS 8110 fire design*. Building Research Establishment/Fire Research Station, Garston, Watford, UK. 2004. 41 pp.
- Cembureau/BIBM/ERMCO. *Improving fire safety in tunnels: the concrete pavement solution*. Cembureau. Brussels, Belgium. April 2004. 8 pp.
- Concrete Reinforcing Steel Institute. *Fire resistance of reinforced concrete buildings*. Engineering Data Report Number 52. CRSI. Schaumburg, Illinois, USA. 2003. 6 pp.
- Concrete Society. *Assessment and repair of fire damaged concrete structures*. Technical Report TR33. Concrete Society. Camberley, Berkshire, UK. 1990. 77 pp.
- Federal Emergency Management Agency. *World Trade Center building performance study*. FEMA Region II, New York, USA. May 2002.
- Horvath, S. *Fire safety and concrete: fire resistance and architectural design*. Cimbeton (Centre for Information on Cement and its Uses). Paris, France. 13 pp.
- Khoury, G. Effect of fire on concrete and concrete structures. *Proceedings of Structural Engineering Materials Journal*. John Wiley & Sons, Chichester, UK. 2000. Vol.2. pp.429-447.
- Kruger, J.E. and Lunt, B.G. *Protection afforded by concrete*. Division of Building Technology, CSIR, South Africa.
- Lunt, B.G. *Civil defence planning and the structural engineer*.
- Neck, U. Comprehensive fire protection with precast concrete elements – the future situation in Europe. In *BIBM 17th International Congress of Precast Concrete Industry: Congress Proceedings*. Turkish Precast Concrete Association, Ankara, 2002. (CD)
- Stollard, P. and Abrahams, J. *Fire from first principles: a design guide to building fire safety* (2nd edition). E & FN Spon, London, UK. 1995. 178 pp.

RELEVANT CODES AND STANDARDS

- Eurocode 2 Part 1.2. *Design of concrete structures; General rules – structural fire design*. BSI, London. 2002. 102 pp.
- BS 8110 *Structural concrete. Use of concrete*, Parts 1, 2 and 3.
- EN 13501-1, *Fire classification of construction products and building elements. Part 1: Classification using test data from reactions to fire tests*. 2002. 44 pp.

ACKNOWLEDGEMENTS

The Concrete Centre wishes to acknowledge assistance from BCA and CEMBUREAU.

PICTURE CREDITS

Front cover	Martin Charles; Design and Materials
Inside front cover	BRE
Page 1	Traditional Housing Bureau
Page 2	Trevor Jones
Page 5	Rastra; BRE
Page 9	CEMBUREAU; Roger Eastell
Page 11	Christeyns UK/Oscrete
Page 12	British Precast
Outside back cover	Trevor Jones



CPD presentations on concrete and fire are available on request.
Please call 0700 4 500 500 or 0700 4 CONCRETE, or email
concreteperformance@concretecentre.com



The **Concrete Centre**™

www.concretecentre.com

The Concrete Centre, Riverside House,
4 Meadows Business Park, Station Approach, Blackwater, Camberley, Surrey GU17 9AB
National Helpline 0700 4 CONCRETE or 0700 4 500 500

Ref. TCC/05/01

ISBN 1-904818-11-0

First published 2004

© The Concrete Centre 2004

All advice or information from The Concrete Centre is intended for those who will evaluate the significance and limitations of its contents and take responsibility for its use and application. No liability (including that for negligence) for any loss resulting from such advice or information is accepted. Readers should note that all Centre publications are subject to revision from time to time and should therefore ensure that they are in possession of the latest version.