INFORMATION BULLETIN: IB 93

Fire Performance of Concrete and Concrete Masonry

CCANZ
concrete answers

CONTENTS

INTRODUCTION

Concrete is generally considered to have good fire resistance since it is non-combustible (i.e. it does not burn), absorbs heat only slowly, and does not give off toxic fumes or smoke. As it is a poor conductor of heat and has a high heat capacity, concrete is used to protect other construction materials such as steel and timber from fire. In addition, it is this slow heat absorption which enables concrete to act as an effective fire shield to protect adjacent spaces and contents, as well as itself from internal fire damage.

These inherent properties, combined with the appropriate design of structural elements, ensure concrete performs well in fire.

However, there are some issues surrounding concrete's performance in fire which require careful consideration. This bulletin outlines these issues, while providing general guidance to designers and specifiers on the design of concrete structures against fire.

PRINCIPLES OF FIRE PROTECTION

The first and most important objective in fire protection is to safeguard the lives of any people who are in the structure which is on fire, and enable them to exit the building quickly and safely. Secondly, the structure must be designed to allow enough time for fire fighters to safely carry out any search and rescue operations, along with firefighting operations. Thirdly, there are requirements to protect other property under the New Zealand Building Code (NZBC), these include preventing the fire from spreading as well as preventing hazardous materials at the fire site entering waterways.

Concrete is commonly used to provide stable firecells in large industrial or multi-storey buildings as a means to contain a fire and prevent it spreading to the whole building. This is also called fire separation or compartmentation. Concrete walls reduce the spread of fire horizontally and concrete floors vertically. Concrete provides the opportunity to install safe separating structures in a reliable and economical way.

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. The three functions of Stability (R), Integrity (E) and Insulation (I) are universally recognised to define fire protection. Time periods (fire ratings) are attributed to each of these functions to designate the level of fire performance. The overall Fire Resisting Rating of an element is termed FRR, thus a FRR of 90/90/90 requires a 90 minute rating for each of stability, integrity, and insulation.

Stability

Stability is the load bearing capacity provided by the primary elements within a firecell and includes elements which are part of the structural frame as well as those providing support to other fire rated elements. The Stability fire rating (R) is based upon the time an element can withstand a standard fire test and retain its loadbearing capacity while allowing for a level of superimposed load.

Integrity

Integrity is the flame arresting separation typically provided by secondary elements e.g. internal walls, to protect people and goods from flames, harmful smoke and hot gases. Primary elements, along with secondary elements, are also rated for integrity. The time during which an element's fire separation capability is maintained is determined by the tightness of joints to limit smoke and gas penetration.

Insulation

Insulation is the heat shielding capability provided by either primary or secondary elements. It is applied to fire separations where the transmission of heat may endanger occupants on the non-exposed side or cause fire to spread to other fire compartments. The fire rating is the time defined by a maximum permitted rise of temperature on the non-exposed side.

ACTIVE VERSES PASSIVE FIRE PROTECTION

Concrete's inherent fire resistance provides a robust passive protection system that usually requires no additional fireproof linings or coatings. Fire protection for lightweight construction often relies on active protection systems such as sprinklers. However, the robustness of sprinkler systems following an earthquake has been questioned in light of the vulnerability of reservoir water supply and the significant risk of a post-earthquake fire.

The integrity of fire linings following an earthquake has also been brought into question by BRANZ research, particularly where dislodged plaster filling at joints, resulting from seismic shaking, compromised the integrity by 40%. In addition, it has also been found that poor workmanship in retrofitting of structures after installation of services through lightweight fire rated elements has compromised subsequent levels of fire protection.

CONCRETE PERFORMANCE IN FIRE

At temperatures of 150°C upwards there is some loss of water from the silicate hydrates in concrete, while temperatures above 300°C result in the loss of bound water, and in turn strength. While concrete may undergo strength loss at temperatures 300°C and above, the main losses are seen until 500 °C upwards. Even though flame temperatures are up to double 500 °C, the temperature of the internal concrete remains relatively low as a result of concrete's slow heat absorption. Therefore, only intense fires of long duration may cause any weakening of concrete structures.

Cement type can have some influence on strength loss. Cements with fly ash and ground granulated blast furnace slag have lower quantities of free calcium hydroxide which can give reduced hydration loss on heating, and consequently lower strength loss.

The fire rating of a concrete is also influenced by the aggregate type. This results partly from the coefficient of thermal expansion between the aggregate and the cement paste being different, particularly at higher temperatures. The thermal conductivity of concrete depends on the nature of the aggregate, porosity and moisture content. As water is driven from the concrete in a fire, the conductivity of the 'dry' concrete is more relevant. Lightweight aggregate concretes in particular, have very good fire performance in 'dry' building fires because they have a thermal expansion closer to cement paste. They also have good aggregate bond and high aggregate temperature stability. Limestone has an additional advantage in that it breaks down at temperatures over 660°C giving off carbon dioxide which provides a blanketing effect against heat penetration.

The effect of aggregate type on fire resistance is demonstrated in the table below. Based on minimum effective slab and wall thicknesses the table shows a range of insulation fire ratings (I) for three different aggregate types.

Fire Resistance rating (minutes)	Effective thickness (mm) for different aggregate types		
	Type A aggregate	Type B aggregate	Type C aggregate
30	50	45	40
60	75	70	55
90	95	90	70
120	110	105	80
180	140	135	105
240	165	160	120

Note: Aggregate types:

A - quartz, greywacke, basalt and all others not listed

B - dacite, phonolite, andesite, rhyolite, limestone

C - pumice and selected lightweight aggregates

Source: NZS4230: 2044

Spalling of the surface concrete is a phenomenon which may occur in certain circumstances where the surface concrete breaks away at high temperatures. This is more common in higher strength concrete, where moisture content and reinforcement cover are more significant. The spalling is caused by internal moisture turning to steam during a fire with a resultant build-up of pressure in the pores of the concrete which cannot escape. Spalling can have a progressive effect on fire performance as it exposes the internal concrete and reinforcement to the heat of the fire. As the use of silica fume in concrete reduces the porosity, this has the potential to increase the risk of spalling.

Fortunately there is a fairly simple solution, which involves adding monofilament polypropylene fibres, at 2kg/m^3, to the concrete. This provides for steam release via the fissures formed when the fibres melt at elevated temperatures.

BS EN 1992-1-2 General – Structural Fire Design states that precautions need to be taken where the concrete strength is above 55 MPa, with additional precautions required where the cover is greater than 70mm or the silica fume content is greater than 6% by weight of cement. The code also gives the critical concrete moisture content above which 'explosive spalling' can occur. In this instance a deeper analysis is required involving the type of aggregate, permeability of the concrete and heating rate.

Reinforcing steel loses strength at elevated temperatures – there is a 15% loss from 350 °C up to 50% at around 600 °C, and an 80% loss at 750 °C. However, concrete's low thermal conductivity protects reinforcing steel from significant temperature gain provided it has sufficient cover. Thus, the specification of minimum cover to reinforcement has to meet both durability and fire performance requirements.

BASIS OF FIRE DESIGN

Standard test methods are used to determine the fire performance of materials or structural elements. These tests may either be at a small scale with a component of a building in an oven or furnace, or at full scale in a mock-up of a fully assembled building subjected to a fire regime.

Standard fire time temperature curves have evolved to represent typical fires experienced in practice. The curves for fires representing three scenarios for building fires, hydrocarbon fires and tunnel fires are shown in *Figure 1*. These curves are different for the different scenarios. For instance, the temperature of a building fire rises much more slowly and peaks at a lower temperature than a hydrocarbon fire from burning vehicles as there is less combustible material present. Tunnel fires have a significantly higher peak temperature owing to the confinement of the fire.

The hydrocarbon load in a tunnel can be considerable, which includes not only vehicles but also the bituminous road surface. As a result, the use of concrete roads in new tunnels is now recommended. *Figure 2* represents a standard furnace time temperature curve for a building fire taken from *AS 1530.4-05 2005 Methods for Fire Tests on Building Materials, Components and Structures (Part 4: Fire-Resistance Tests of Elements of Building Construction).*

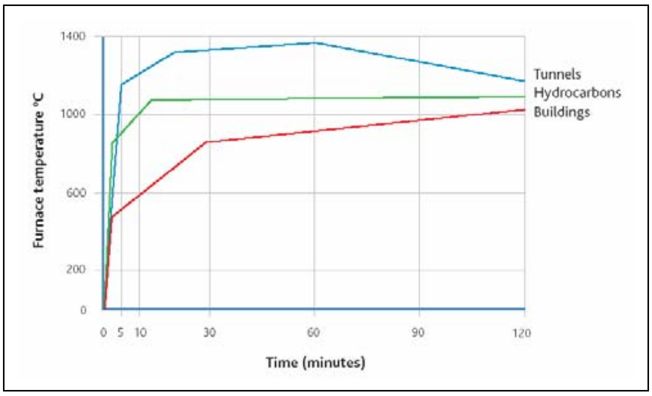

Figure 1: *Standard fire curves for three scenarios – tunnels, hydrocarbons and buildings*

Source: Concrete and fire safety. UK Concrete Centre (2008)

The *NZS 3101:2006 Concrete Structures Standard* and the *NZS 4230:2004 Design of Reinforced Concrete Masonry Structures* cite *AS 1530.4-05 2005* as the compliance code for carrying out fire tests on building components or assemblies. This code gives a standard time-temperature curve. This will differ from the time temperature relationship in an actual fire as controlled by a number of factors – fuel, fuel geometry, ventilation and restraint provided on members from adjacent areas of the building which are unaffected by the fire.

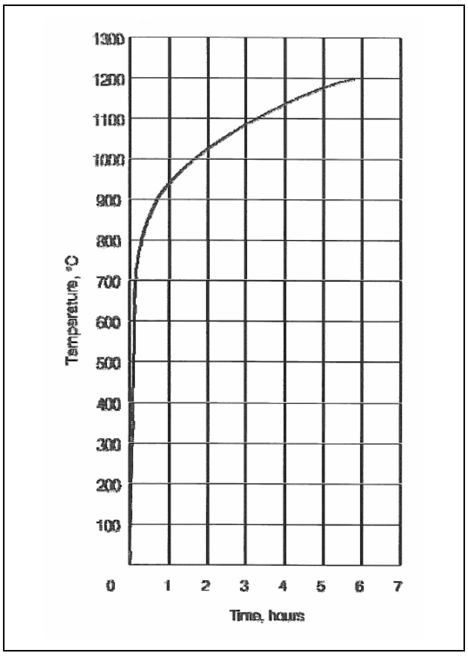

Figure 2: *Standard furnace temperature-time curve*

Source: AS 1530.4-05 2005

The increasing sophistication of computer modelling techniques has enabled data from standard fire tests on building components to be interpolated into the predicted fire behaviour of building assemblies and whole buildings. This has had the effect of reducing the need for comprehensive whole assembly fire tests of buildings.

NZBC FIRE SAFETY REQUIREMENTS

NZBC Compliance Document Clause C Fire Safety sets out four objectives for meeting fire safety requirements. These are:

- C1: Outbreak of fire - Safeguard people from illness or injury caused by fire.
- C2: Means of escape - Safeguard people from illness or injury whilst escaping and facilitate fire rescue operations.
- C3: Spread of fire – Protect adjacent dwellings and other property from the effects of fire and safeguard the environment from the effects of fire.
- C4: Structural stability – Safeguard people and adjacent dwellings and property from structural instability caused by fire.

In clause C2 the functional requirement for means of escape is as follows:

Buildings shall be provided with means of escape from fire which:

(a) Give people adequate time to reach a safe place without being overcome by the effects of fire and

(b) Give fire service personnel adequate time to undertake rescue operations.

The NZBC does not set the requirements for a specific FRR of a building or other fire safety features as can be seen from the description of the functional requirement for means of escape given above. These are however, outlined in Acceptable Solution C/AS1, which is prescriptive in terms of the fire safety requirements. The FRR applicable to a particular situation is typically chosen based on the purpose group, the height of the building, the occupant load and the fire hazard category. As an acceptable solution this is a 'deemed to comply' solution, other specific design solutions can be submitted but require verification.

The material used for structural and separating elements has to be designed to resist the effects or passage of fire. The specific requirements are given by their F (firecell) or S (structural endurance) rating. The F rating of a specific construction element is designed to prevent the spread of fire to another firecell. F ratings apply to both loadbearing and non loadbearing elements in a firecell (walls, floors and their supports). The S rating is to prevent fire spread or structural collapse for the complete burnout of the firecell. It usually applies to a structural member on or near a boundary where there is a requirement that a wall or floor does not collapse as a result of a fire. The collapse of any part of the building must not cause the collapse of the S rated wall or floor during the fire's duration. Thus an S rating is usually more stringent than an F rating.

For a building design (excluding boundary protection measures) the highest fire safety rating required by the Acceptable Solutions is F90 and is for buildings over 58m high (unless a specific design is being used, in which case the fire rating could be higher). The most common rating is F60 for two or more floors of a building without automatic fire sprinklers. The F rating is required between levels and for protection of escape routes. With automatic fire sprinklers fitted the F rating can be halved in some cases.

Fire Hazard Category (FHC) is used to classify purpose groups or activities having similar fire hazard, and where fully developed fires are likely to have a similar impact on the structural stability of the building. As examples, FHC 1 applies to low risks, such as ground floor structures manufacturing non-combustible materials, whilst FHC 4 applies to chemical manufacturing plants. Table 5.1 of Acceptable Solution C/AS1 sets out the required S rating for buildings up to FHC 3, which is dependent on the ventilation of the building for a given FHC i.e. the fire load. A well ventilated building will burn faster and hence the S rating is lower than that required for a building with little or no ventilation. Note that glazed windows are considered as open vents as they generally fail early in a fire.

FHC 4 buildings require specific design to determine the duration of the fire burn and hence the S rating.

Most S rated boundary walls utilise concrete for its superior toughness, good fire rating and being structurally sound, as well as having good Spread of Flame Index (SFI) and Smoke Developed Index (SDI) properties, which are satisfactory for the worst case scenario. High-rise apartments are generally concrete structures and the fire escapes (deemed safe places) are concrete enclosed, usually bare, to comply with the need to have no combustibles within the space.

In the design of a multi-level building, each level is a separate firecell. Hence penetrations through the floor must be protected against the passage of fire by the installation of a suitable fire stopping mechanism. The most common need for floor penetrations is to distribute services up the building. Services on each level do not require any further fire protection unless there is a special case to warrant it. Another alternative is to provide a fire rated shaft running up the building with all services in it. This requires the services taken from the shaft onto each level to be protected with a suitable fire stopping mechanism.

In non-sprinkler protected buildings, walls and ceilings require limitations on the surface finishes for SFI and SDI indexes. These are dependent on the purpose group and location within the building. The purpose of these indices is twofold:

a) Stop the rapid spread of flame across a surface

b) When the combusted amount of smoke generated is controlled and not likely to reach untenable conditions during the time of escape.

Surface finish requirements apply also to roof underlays when exposed to a fire, to floor coverings in certain instances, and to HVAC ducting for both internal and the exterior surfaces.

STRUCTURAL FIRE DESIGN

Concrete

NZS 3101:2006 The Concrete Structures Standard sets out design requirements for determining the fire resistance ratings of concrete elements required by the NZBC. Fire design is based on the *Tabular* method which gives minimum dimensions for beams, columns, walls and slabs for structural adequacy and insulation. Also included is the minimum reinforcement depth for fire rating, which is referred to as the axis distance based on a calculated average distance to the centroid of the main reinforcement.

The following tables are extracted from Section 4 of NZS 3101:2006 for floor slabs and load bearing walls. In the case of load bearing walls, as the axial load as a proportion of the load capacity increases, the required wall thickness increases. The axis distance is also given. This ensures that the steel has adequate protection from the heat of a fire by cover concrete.

Table 4.3 of NZS 3101: 2006 gives effective slab thickness based on FRR for insulation, which also applies to partition fire rated walls. Table 4.9 of NZS 3106: 2006 is based on FRR for structural adequacy of load bearing walls where:

a = the required axis distance,

b = the wall width, and

η_{fi} = the ratio of the factored design axial load under fire conditions (n^*_t) divided by the axial load capacity at normal temperature (N_u).

NZS 3106: 2006 also refers to the use of either simplified or advanced calculation methods detailed in *Eurocode 2: Design of Concrete Structures Part 1-2: General Rules-Structural Fire Design BS EN 1992-1-2:2004.* Further guidance on these methods is provided by the UK Concrete Centre publication *How to Design Concrete Structures Using Eurocode 2 – Structural Fire Design.*

FRR for Insulation *(minutes)*	***Effective Thickness*** *(mm)*
30	*60*
60	*75*
90	*95*
120	*110*
180	*140*
240	*165*

Source: NZS 3101:2006. Table 4.3 Fire resistance criteria for insulation for slabs

Fire resistance rating (minutes)		**Minimum dimensions** (mm)	
		Wall exposed to fire on one side	
		η_{fi} = 0.35	**η_{fi} = 0.7**
30	b a	100 10	120 10
60	b a	110 10	130 10
90	b a	120 20	140 25
120	b a	150 25	160 35
180	b a	180 40	210 50
240	b a	230 55	270 60
Column 1	2	3	4

Note:

(1) $\eta_{fi} = N^*_t/N_u$ see 4.6.2.

(2) *For prestressing tendons the increase in axis distance given in 4.3.3 shall be noted.*

Source: NZS 3101:2006. Table 4.9 Fire resistance for structural adequacy for load-bearing walls

Concrete Masonry

NZS 4230:2004 sets out design requirements for concrete masonry. These are based on British and European documents published by BSI and CEB/FIP. It gives minimum dimensions for walls, beams and columns based on structural adequacy and insulation. The effective thickness of partially filled masonry walls needs to be adjusted downward by dividing the net cross-sectional area of the wall by the length of the wall. Also, the cover depth for masonry walls has to be taken from the inside of the faceshell.

However, it is over 6-years since NZS 4230 was published and more up to date material is available in *Eurocode 6: Design of masonry structures Part 1-2: General rules-Structural fire design BS EN 1996 -1-2:2005*. This standard is based on a *tabular* method for masonry structures. In the same way as Eurocode 2, the required wall thickness increases as the axial load increases. In addition, plastering of a masonry wall increases the effective fire rating.

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 the use of a performance based approach using advanced calculation methods which lead to more economical, robust and innovative concrete buildings.

Analytical computer based modelling of whole buildings utilise the interaction between building elements which can result in structures being safer than calculated in design based on individual structural elements. For example, when a concrete slab expands under high temperatures to push outwards against its supports, a mechanical arching effect takes place in the slab. The compression generated in the bottom of the slab can greatly increase the load capacity.

External Walls

Section 4.8 of NZS 3101: 2006 gives particular requirements to prevent collapsing external walls outwards in a fire. The loadings code requires free standing external walls to be designed to resist a face load of 0.5 kPa in the after fire condition. When a fire occurs inside a building, the interior face of the wall heats up and expands while the exterior face remains relatively cool. Coincidentally the eccentricity of axial load on the wall causes additional deflections due to the P-delta.

The wall has the potential to collapse when the actions on the wall due to thermal bowing and P-delta effect can lead to the wall's capacity being exceeded effect – see *Figure 3*. Such a collapse into adjoining property risks placing fire crews or neighbours in danger. A base-cantilever-resisting mechanism is usually required to prevent collapse.

A wall connected to a very weak or flexible roof structure will need to be designed with a cantilever base connection. The design of the unprotected mild steel connections needs to be based on 30% of the yield strength of the exposed steel in ambient conditions. Components made from other types of steel shall use mechanical properties of the steel at 680°C. Details for FRR ratings and fixing of proprietary inserts are given in the standard. Adhesive (glued) anchors are have been found to behave poorly at elevated temperatures and need to be protected from fire.

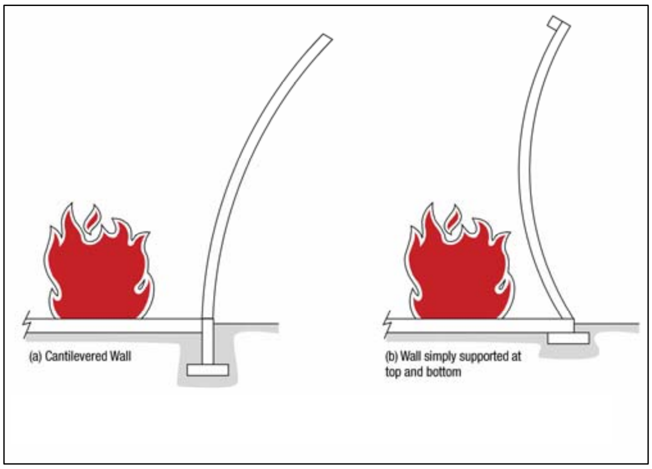

Figure 3: *Deformation profile caused by heating one side of the wall*

Recent research has been carried out on slender panels by BRANZ and the University of Auckland owing to a concern of the high slenderness ratios of on-site and off-site precast panels being used in practice. A range of slenderness ratios from 30 to 75 were investigated. NZS 3101:2006 places a slenderness ratio limit of 75. Other maximum slenderness ratios have been proposed.

INSURANCE AND FIRE DAMAGE

A recent, independent European investigation on the cost of fire damage in relation to the building material from which houses are constructed used statistics from the Insurance Association in Sweden (Forsakrings Forbundet). The study was on large fires in multi-storey 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 involving 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

The time taken to repair a building after a fire is important in terms of downtime for commercial businesses. Concrete and concrete masonry buildings are generally easier and quicker to repair. In buildings subject to arson attack such as schools, the loss of contents and repair time is also critical. These losses can be significantly less in concrete and concrete masonry buildings.

In the UK there have been a disproportionate number of fires in timber structures under construction. The fire load of a timber building being constructed is significant, and cannot be contained effectively until compartmentation is completed. In a concrete and concrete masonry structure the fire load during construction is significantly less.

CONCLUSIONS

The excellent performance of concrete and concrete masonry structures in fire is widely accepted. The role of concrete in providing passive fire protection gives a significant advantage over steel and timber structures and provides a more robust solution to fire protection. The behaviour of concrete in fire is well understood, and is substantiated by a wealth of fire testing research data.

Concrete design standards have historically been based on prescriptive data generated from fire tests. Eurocode 2 outlines an alternative approach based on computer simulation and performance based fire-safety engineering. This allows a greater degree of flexibility in terms of sizing concrete elements for fire safety and will lead to the more efficient design of concrete and concrete masonry structures.

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