ArupFire

HSE

# Fire resistance of concrete enclosures

Work Package 1: data collection
Work Package 2: spalling categories

Rev B

ArupFire

HSE

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Work Package 1: data collection
Work Package 2: spalling categories

October 2005



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Job number 116718

| | | | |
|---|---|---|---|
| Job title | 0001Report Work Package 1 and 2 11th October 2005.doc | Job number | |
| Document title | Report Title | File reference | |
| Document ref | | | |

| Revision | Date | Filename | 0006Report draft 3.doc | | |
|---|---|---|---|---|---|
| Draft for review | 11/11/04 | Description | First draft | | |
| | | | Prepared by | Checked by | Approved by |
| | | Name | | | |
| | | Signature | | | |
| Issue | 29/11/04 | Filename | | | |
| | | Description | Incorporating HSE comments raised at Design review 19th Nov 2004 | | |
| | | | Prepared by | Checked by | Approved by |
| | | Name | Rachel Yin/Susan Lamont | Barbara Lane | Barbara Lane |
| | | Signature | | | |
| Rev A | 01/12/04 | Filename | | | |
| | | Description | Incorporating minor changes for HSE | | |
| | | | Prepared by | Checked by | Approved by |
| | | Name | Rachel Yin/Susan Lamont | Barbara Lane | Barbara Lane |
| | | Signature | | | |
| Rev B | 11/10/05 | Filename | 0001Report Work Package 1 and 2 11 October 2005 | | |
| | | Description | 0001Report Work Package 1 and 2 11th October 2005.doc | | |
| | | | Prepared by | Checked by | Approved by |
| | | Name | Susan Lamont | Barbara Lane | Barbara Lane |
| | | Signature | | | |

Issue Document Verification with Document ✓

## CONTENTS

# 1 Executive summary

This document and associated files in the database (see Appendix A for a description of the database) form the submission for Phase 1, work packages 1 and 2 of the project "Fire resistance of concrete enclosures" for the Nuclear Safety Directorate of the Health and Safety Executive (HSE).

This submission is the first phase of a structural fire engineering approach to assess the fire response of concrete structures, specifically enclosures, to external hydrocarbon type pool fires. The intent of the project is to quantify the required thickness of concrete to provide adequate insulation to a concrete enclosure from an external fire.

In general the enclosures will be built from ordinary strength, normal weight concrete.

Work packages 1 and 2 can be summarised as follows;

**Work Package 1**

*Collate available data on spalling and material testing of the thermal properties (conductivity, specific heat and density) of concrete and its constituent materials. This information will be used to create a database of material properties for different concrete types that can be used in the FE heat transfer models in work packages 3-5.*

**Work Package 2**

*Based on the results of work package 1 the range of concretes expected to be used on a nuclear site for enclosures will be categorised into a small number of spalling risk groups (high, medium and low). The groups are expected to be categorised by aggregate type, % moisture content, thermal expansion and concrete strength.*

*An estimated thickness of spalling will be assigned to each risk group based on conservative assumptions about the data from work package 1.*

As a result of the literature review additional factors affecting spalling have been considered in work package 2 these include, section thickness, loading, presence of reinforcement and the number of sides of the concrete section exposed to fire.

There is limited data on spalling of normal weight, ordinary strength concrete in response to a hydrocarbon fire, which is the scenario to be considered in this project. However, there is more test data on spalling of normal weight concrete in a standard fire and of high strength concrete in a hydrocarbon fire. Therefore, there has been a slight change to the brief and five categories of spalling are proposed encompassing the available test data. It can then be determined under what category the HSE directed concrete types requiring assessment, fall.

The conclusions of Work Package 1 are as follows;

- The thermal properties of concrete and its constituent materials are well documented in the literature.
- The density for different normal weight concretes varies between 2000 ~ 2600 kg/m³ at ambient temperature and decreases to 1500 ~ 2300 kg/m³ at 900 °C.
- Different aggregates have different densities, which do affect the concrete density.
- The conductivity for different normal weight concretes varies between 0.8 ~ 2.6 W/mK at ambient temperature and decreases to 0.5 ~ 1.3 W/mK at 1000 °C.
- The specific heat of concrete varies between 750 ~ 920 J/kgK at ambient temperature and increases to 930 ~ 1230 J/kgK at 1000 °C. There is no significant difference between the specific heat of siliceous and calcareous concretes.

These values will be used in the planned heat transfer modelling in Work packages 3-5 of this project.

For each risk category, spalling thicknesses have been defined in this document based on the available limited data from fire tests.

Five categories of spalling risk (very low, low, medium, high and very high) have been defined based on fire exposure, concrete characteristics, loading and restraint conditions, all as formed part of the available test data only.

The level of confidence in the spalling thickness quantification, for each risk category, is discussed in the main body of this document. Confidence levels are bounded by the available test data. Therefore as the project progresses and as further data become available [note we continue to receive test data from various sources world wide] the spalling thickness and/or risk categories will be refined, if necessary.

The five spalling categories have been defined as shown in Table 1.

**Table 1** Risk categories and associated spalling levels

**(*key factors = properties of the concrete or the boundary conditions that are known to promote spalling e.g. aggregate type, section thickness, compressive load etc, see section4.2 for detailed information)**

| Category | Risk of spalling | Key factors | Spalling level |
|---|---|---|---|
| A | Very low | Ordinary strength, NWC, Unloaded, Unrestrained, Standard fire exposure, Reinforced, moisture <3%, one side exposure | Zero or minimal |
| B | Low | Ordinary strength, NWC, restrained, Standard fire exposure<br>Significant number of key variables* likely to promote spalling | Up to the level of the reinforcement |
| C | Med | Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure<br>:Small number of key variables* likely to promote spalling | 3mm/min |
| D | High | Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure<br>Significant number of key variables* likely to promote spalling | 7mm/min |
| E | Very high | High strength (Design strength >55Mpa), standard hydrocarbon fire exposure. | Unquantifiable |

Using Table 1 therefore, the example concrete enclosure provided to Arup by the HSE on Oct. 13, 2004 would be categorised as C, medium risk, as it is normal strength concrete with a design strength of 21MPa, normal weight concrete of average density 2383kg/m$^3$. The aggregate is calcareous limestone.

It is important to note the limitations of the data from which the risk categories and their associated spalling quantification have been derived;

- There are only a small number of tests carried out using NW (Normal Weight), ordinary strength concrete exposed to hydrocarbon fires.
- There is significantly more test data available on the response of high strength concrete exposed to hydrocarbon fires. Indeed the severe spalling of high strength concrete prompted spalling research, so this has resulted in a lack of data on other concrete forms.
- As a result of Building Regulations for fire resistance there is significantly more test data for ordinary strength concrete exposed to the standard fire in BS 476 or ISO 834 than for the standard hydrocarbon fire exposure.
- In almost all published research projects where concrete sections have been tested under fire conditions the presence or not of spalling is reported but the depth of spalling is rarely measured.
- Similarly in design guidance, BS 8110 and Eurocode 2 states whether spalling is likely or not, given a particular set of conditions, it does not offer guidance on spalling rates.

# 2 Introduction

This report summarises the findings of Work Package 1 and 2 of the project “Fire resistance of concrete enclosures” for the HSE.

For work package 1, thermal properties (conductivity, density, specific heat) have been extracted from available research projects and literature in the public domain for different concretes, aggregates and cement pastes. This information is tabulated in the spreadsheets for work package 1 in the database (see Appendix A) alongside comments about the test conditions in which these properties were measured. This data base will be updated as the project continues.

In work package 2, five risk categories have been developed based on concrete types and associated boundary conditions from the created database. A list of the limitations and assumptions made when categorizing the quantity of spalling expected for a specific risk category is also provided.

Predicting spalling for design purposes is not an easy task due to the complex nature and number of variables involved in the process. Therefore it has not been attempted before to quantify the process.

It is important to note that published information about the influence of key properties, such as moisture content, on spalling can often be contradictory. Where this is the case this has been highlighted in this report.

# 3 Summary of database of thermal material properties

A literature survey of 80 papers and reports has shown reasonable agreement in the values of density, conductivity and specific heat for various types of normal weight, ordinary strength concrete and associated aggregates.

The papers and reports are listed in the references section of this report and throughout the database. The data taken from these publications is presented in full in the data base. The layout of the database is described in Appendix A, which contains files –Aggregate properties.xls, Cement properties.xls, Concrete properties.xls and Spalling.xls. Aggregate properties.xls, Cement properties.xls and Concrete properties.xls list the properties of aggregate, cement and concrete respectively. Each individual file contains spreadsheets listing available test or research data of compressive strength, thermal expansion, specific heat, conductivity, density, porosity and moisture content.

Arup spalling.xls contains research findings and test data about spalling of concrete.

The findings of this work can be summarised as follows:

- The density of concrete decreases with temperature.
- The density for different normal weight concretes varies between 2000 ~ 2600 kg/m³ at ambient temperature and decreases to 1500 ~ 2300 kg/m³ at 900 °C.
- Different aggregates have different densities, which will affect the concrete density. However, concrete density will also depend on cement mix. Concrete using a light weight aggregate (e.g. expanded shale) has a low density. For normal weight concretes, density is in the range mentioned above.
- The conductivity of concrete decreases with temperature.
- The conductivity for different normal weight concretes varies between 0.8 ~ 2.6 W/mK at ambient temperature and decreases to 0.5 ~ 1.3 W/mK at 1000 °C.
- Concrete containing quartz has a higher conductivity, therefore siliceous aggregate has higher conductivity than calcareous concrete. Conductivity of concrete increases with increased moisture content.
- The specific heat of concrete varies between 750 ~ 920 J/kgK at ambient temperature and increases to 930 ~ 1230 J/kgK at 1000 °C. There are peaks in specific heat when moisture evaporates at 100°C and at around 500 ~ 700 °C as a result of a chemical phase change. There is no significant difference between the specific heat of siliceous and calcareous concretes.

This information will be used for the heat transfer analyses in Work packages 3-5 in Phase 2 and 3 of this project.

# 4 Factors affecting spalling

Concrete should behave well at high temperatures. The advantages of concrete in a fire are two-fold. It is: incombustible (e.g. when compared with wood); and a good insulating material possessing a low thermal diffusivity (heat cannot pass through it easily, e.g. when compared with steel), which decreases with increasing temperature. However, a major disadvantage of concrete is spalling. Spalling is the breaking off of layers or pieces of concrete from the surface of a structural element when it is exposed to high and rapid rising temperatures experienced in fires. There are many types of spalling and these are discussed in Section 4.1 of this report. Explosive spalling is the most aggressive type and is due to a combined action of pore pressures created as moisture evaporates and high stresses as the hot material tries to expand against its surroundings including adjacent cooler concrete or initial loading. It is dependent on aggregate, moisture content, stress level, heating rate and temperature amongst other variables.

Spalling may be insignificant in amount and consequence, such as surface pitting or it can seriously affect the stability of the construction because of the extensive removal of concrete from reinforcement or because it causes holes to appear in slabs or panels, which can result in instability or failure of containment function. It can occur soon after exposure to heat, accompanied by violent explosions, or it may happen when the concrete has become so weak after heating that cracks develop and pieces fall off the surface.

## 4.1 Types of spalling

There are many types of spalling including:

- Explosive spalling – This type of spalling occurs during the early part of a fire, usually within the first 30 min or so of a standard furnace test. It can occur at an early stage just above 100°C. It is characterised by large or small pieces of concrete being violently expelled from the surface, accompanied by a loud noise. The pieces may be as small as 100mm or as large as 300mm in length and 15-20mm deep (CIRIA 1984). The phenomenon can occur just once or at intervals even from the previously spalled parts. Multiple spalling layers is more likely in High Strength Concrete (HSC) than Ordinary Strength Concrete (OSC) (Khoury 2003). Occasionally, the severity of explosive spalling can lead to the formation of holes through the thickness of the section. In many cases, this type of spalling is restricted to the unreinforced part of the section and usually does not proceed beyond a reinforcing layer (CIRIA 1984).
- Surface spalling – This type of spalling is associated with local removal of surface material including, pitting and blistering. This occurs when small pieces, up to about 20mm in size, fly off the surface of a concrete element during the early part of its exposure to a fire or a fire test. Surface spalling may result in exposure of the reinforcement (Khoury 2003).
- Aggregate splitting – This type of spalling is failure of aggregate near the surface, characterized by a popping sound. It is caused by thermal expansion of the aggregate and splitting of pieces of aggregate close to the surface because of physical or chemical changes, which occur at high temperatures in aggregates. The main causes are limonite-haemetite conversion of quartz at 570°C (CIRIA 1984). It has little impact on structural performance as the majority of the cover remains intact and insulates the reinforcement. In addition, because aggregate spalling only causes superficial damage to concrete, the insulation function of the structural members in fire is little affected.
- Corner separation - This type of spalling occurs during the later stages of a fire exposure when the concrete has become weak and cracks develop as a result of tensile stress along edges and corners where the reinforcement is typically located.

Pieces of concrete fall off of beams and columns, and may be followed by pieces coming away from the faces as cracks develop further. Because of the advanced stage at which such spalling occurs, the strength of the element may have already reduced significantly, and therefore this type of spalling may be of limited significance to structural stability because it has already been lost.

- Sloughing off – This is a gradual progressive process which is caused by chemical deterioration of cement paste and internal cracking of concrete due to the difference in thermal expansion between the aggregate and the cement paste (Breunese and Fellinger 2004). This type of spalling is related to the attained temperature of concrete and not the heating rate which tends to define explosive spalling.
- Post cooling spalling –This is a non-violent process with no sound and is caused by carbonate aggregates in Limestone expanding on re-hydration during the cooling phase of a fire.

Research to date suggests explosive spalling is the most significant form of spalling when the heating rate is rapid e.g. a standard hydrocarbon fire (Marsh 2002). The significant loss of material during explosive spalling leads to a more rapid rise of temperature in the remainder of the section and a reduction in the load bearing and containment functions of the element.

It is this form only that is considered within this assessment.

## 4.2 Factors that influence spalling

Spalling is influenced by a number of factors; rapid heating, the heating profile, chemical composition of the cement, aggregate type, large compressive stresses, loading, restraint to thermal expansion, pore pressures as a result of moisture expanding on evaporation. The factors that affect spalling derived from the literature review carried out for this Work Package are discussed in the following sections and were all considered when determining the risk categories.

### 4.2.1 Moisture content

Moisture content is one of the main factors causing spalling. In the absence of moisture, the likelihood of explosive spalling is reduced (Schneider 1986). However, explosive spalling due to thermal stress can still occur with no moisture in ceramic materials for instance (Khoury 2003).

Many researchers have shown that increasing moisture content increases the probability of spalling. Therefore, concretes in wet conditions (e.g. an external environment) will tend to spall faster and more extensively than a drier concrete. This is because the moisture increases the thermal conductivity and therefore the rate at which the concrete responds to heating and the rate of production of water vapour that builds up inside the concrete, which leads to earlier spalling (SINTEF 1988).

It is commonly accepted that constructions of traditional concrete (normal weight, ordinary strength) with less than 3% moisture content by weight will not give rise to explosive spalling and that traditional concrete in the range of 3-4% moisture content has a limited risk of spalling (Hertz 2003, Newman and Choo 2003, EC2). However, spalling has been observed in some limited instances at low moisture content (<3%) (Shuttleworth 1997).

The database produced as part of this project lists 4 separate sets of experiments where spalling was observed at moisture contents less than 3% (see Table 2).

| **Test reference** | **Test sample** | **Tests conditions** | **Spalling (mm)** | **Moisture content (%)** | **Significance** |
|---|---|---|---|---|---|
| Shuttleworth (1997) | C60, unstressed slab | 2 hour ISO 834 standard fire | 5-20mm | 2.1-2.9 | Observed in3 tests. |
| Both (2000) | C75-C86, prestressed | RWS fire curve | 22-50 | 2.9-3 | Observed in 2 tests |
| SINTEF (1992) | HSC | Hydrocarbon fire | 41mm | 2.9 | Observed in 1 test |
| Thomas and Webster (1953) | C25-C30 columns | BS 476 standard fire | Cracking and sloughing of corners | 1.8-2.4 | Observed in 11 tests |

**Table 2** Tests listed in the database “spalling.xls” where spalling is observed in concretes with moisture contents <3% by weight.

The tests by Both (2000) and SINTEF (1992) were carried out on high strength concretes where the 3% rule of thumb is for normal strength concretes.

Sloughing off of concrete at the corners of the columns in the tests by Thomas and Webster (1953) is caused by chemical deterioration of the cement paste and internal cracking of concrete due to the difference in thermal expansion between the aggregate and the cement paste. It is a gradual process and not thought to be as a result of moisture.

The tests by Shuttleworth (1997) are significant in that spalling was observed in normal strength concrete at a moisture content of just over 2%. However, the amount of spalling during 2 hours of the standard fire was only 5-20mm.

From the test data presented in “spalling.xls” there is only 1 instance where explosive spalling occurred in normal weight concrete at moisture contents below 3% by weight. The amount of spalling observed was 5-20mm. When compared to the spalling rates proposed for this project (see Section 5.2 of this report) of 3mm/min (=180mm in 2hours) the amount of spalling observed in the test is small. This one case of spalling below a moisture content of 3% is not considered to negate the 3% rule of thumb referenced by many (BS8110-2 1985, Khoury 2000, Newman and Choo 2003, Hertz 2003, Lennon 2004, CIRIA 1984).

In some literature, the moisture content is expressed in terms of relative humidity of the concrete. Higher relative humidity levels lead to greater spalling. The acceptable relative humility level of concrete to reduce the spalling risk is 75% (Kodur 1999).

#### 4.2.2 Water/Cement ratio, Permeability

Cement paste with a low water cement ratio, produces a dense almost impervious microsturcture (Komonen and Vesa 2003), which keeps the moisture vapour from escaping in a high temperature environment. This can lead to a build up of high internal pore pressure in the cement paste. Consequently the concrete is more likely to explosively spall, and to experience multiple spalling.

High strength concrete (HSC) normally has a low water/cement ratio, therefore is more likely to spall when compared to normal strength concrete.

Permeability is especially important in fires of high heating rate, such as hydrocarbon fires because the low permeability will trap moisture and pressure will build up rapidly under rapid heating causing spalling.

#### 4.2.3 Heating condition

The heating condition is also one of the major factors influencing spalling. Spalling is much more severe in fires characterized by fast heating rates or high fire intensities due to the large temperature increase and moisture gradient in the fire-exposed parts (Kodur 1999). Hydrocarbon fires pose a severe threat in this regard. Explosive spalling seems to be the dominant spalling form in a hydrocarbon type fire (Marsh 2002).

In addition, heating of more than one side of a concrete section (e.g. 4 sides of a column) increases the probability of spalling (Schneider 1986, SINTEF 1988, Lennon 2000).

#### 4.2.4 Aggregate

For normal weight concrete, there are two common aggregate groups: siliceous aggregates such as quartzite, gravel, granite and flint; calcareous aggregates such as limestone, dolomite and anorthosite (see file “aggregate properties.xls” in the database for more information).

It is widely found that siliceous aggregates give the poorest resistance to spalling (Newman and Choo 2003). Flint aggregate is particularly susceptible (Canisius *et al* 2003). This can be explained partly as a result of the markedly different coefficients of thermal expansion between aggregate and cement paste, particularly at higher temperatures, and partly the result of a volume increase phase transformation (at approximately 570°C) from $\alpha$-quartz to $\beta$-quartz (see database). Expansion of the aggregates leads to cracks in the concrete or splitting of the aggregate which contribute to spalling.

Calcareous aggregates tend to give good fire performance (Newman and Choo 2003). There are several reasons to explain the improved resistance to spalling. First, the calcareous aggregates typically have a lower coefficient of thermal expansion than siliceous aggregates and they are closer to that of cement paste, producing lower internal stresses on heating. Secondly, there are no solid state phase changes in calcareous aggregates within fire exposure conditions.

On heating to temperatures in excess of 660°C calcium carbonates begin to break down, similarly above 740°C for magnesium carbonates. On breaking down the minerals release carbon dioxide and heat transfer is claimed to slow down despite the reaction being endothermic. The residual aggregate particles also have lower thermal conductivity, further reducing heat transfer into the concrete. During cooling the carbonates, which have broken down during heating, re-hydrate. This re-hydration reaction is believed to cause post-cooling spalling in calcareous aggregate concretes (Khoury 2003).

Design guidance on cover and thickness of section based on the standard BS 476 fire exposure is purely empirical and has changed at regular periods since the late 1940s as more tests were carried out. Before 1972 the beneficial effects of calcareous aggregates were represented by the code CP110. As a result of tests reported in a National Building Studies report where any benefit of calcareous aggregate was not observed the 1972 code omitted design guidance specific to calcareous aggregate. This has not changed in modern tabulated design guidance for cover and section thickness (BS 8110 Part 2).

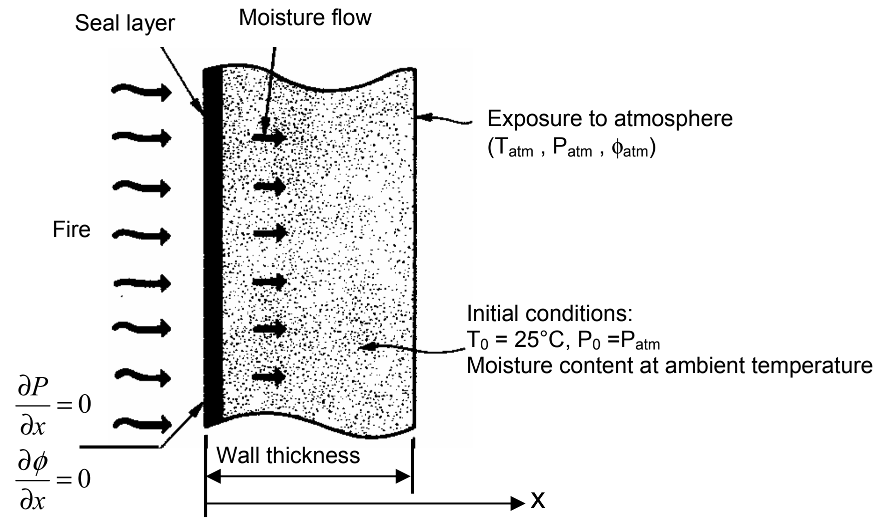
#### 4.2.5 Test condition

Concrete is usually tested at high temperatures in sealed or unsealed conditions, in which the unsealed test condition is closer to reality with respect to a concrete building in a fire. In an unsealed test, vapour can escape from the concrete surface. In a similar manner to a wall or a slab in a building fire. In a sealed test, water vapour and pore pressure gradient at the fire exposed surface equal 0 (Huang et al 1991). Figure 1 illustrates the difference between sealed and unsealed test conditions. The primary difference is that moisture can escape towards the fire in an unsealed test but is forced to migrate through the concrete in a sealed test.

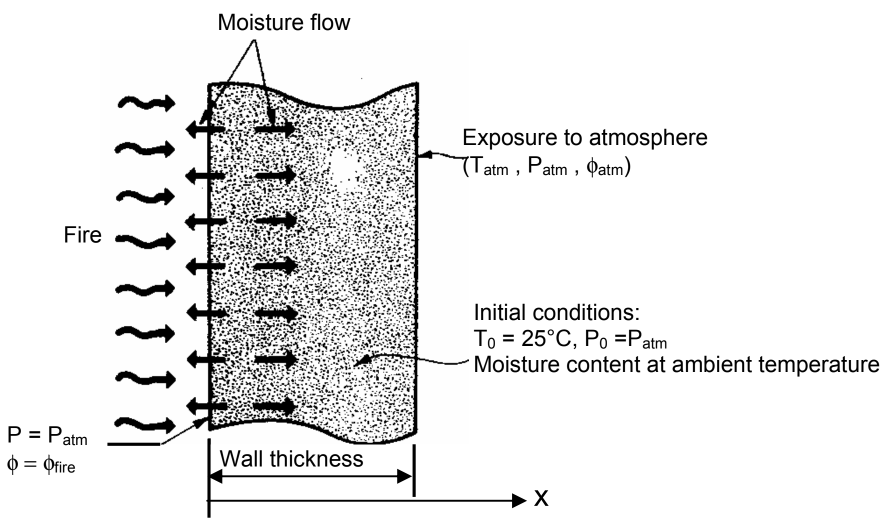
A sealed test is commonly carried out to test concrete pressure vessels used in the nuclear industry where there is a barrier between the concrete and the heating regime preventing moisture escaping towards the heat source.

The dominant process for unsealed concrete relates to the loss of the various forms of water (free, absorbed and chemically bound), while the dominant process in sealed concrete relates to hydrothermal chemical reactions (Khoury 2000)

A mathematical model, simulating the heat and mass transfer in concrete structures under fire (Huang et al1991), has shown that in both sealed and unsealed test conditions, the pore pressure builds up rapidly across the drying region of the concrete section as a result of high heat flux from the fire and low mass transport capacity of the heated concrete during the developing period of fire exposure. Consequently, spalling of concrete is expected in the early stages of the fire (typically the first 20 minutes) when the pore pressure exceeds the ultimate tensile strength of the concrete. Pore pressure then reaches a constant or dissipates during the steady state and cooling phase of the fire. Similarly spalling as a result of thermal expansion will reduce because the temperature change slows down in the steady state phase.




(a) Sealed concrete slab in fire




** P: Total pressure or pore pressure
T: Temperature
$\phi$: water vapor

(b) Unsealed concrete slab in fire

**Figure 1** Sealed versus unsealed tests conditions (Huang *et al* 1991)

#### 4.2.6 Concrete strength

Spalling in part is attributed to the build up of pore pressure during heating. High strength concrete is more susceptible to this pressure build up, because of its low permeability, which inhibits the escape of water vapour, compared to that of normal strength concrete. Available information (Kodur 1999) shows that concrete with strengths higher than 55MPa are more susceptible to spalling and may result in lower fire resistance.

In normal strength concrete, the vapour can be transported much more easily to the unexposed surface reducing the risk of spalling.

There can be significant variation between the design strength specified for a particular concrete and the actual strength achieved on site. Indeed 95% of the concrete samples tested on site should achieve a strength greater than the design strength. The variation in strength could be up to 20% or more.

However, concrete mixed on site that has a higher strength than its design strength is not the same as high performance concrete with silica fume and very low permeability, which is very susceptible to spalling.

#### 4.2.7 Section size

Section size is also an important factor affecting spalling - with thick members the probability of spalling decreases. CIRIA (1984) concluded that beams of 200mm or greater are less likely to suffer serious spalling. A design nomogram in EC2 suggests spalling is unlikely for members with section size >200mm.

Most variables that affect spalling are inter-related. Test results (CIRIA 1984) show that explosive spalling is unlikely to occur if the moisture content of concrete is below 2.5% by weight and the concrete section not less than 80mm thick. For specimens about 120mm in thickness, the moisture content can be as high as 4.5% before spalling occurs.

#### 4.2.8 Applied Load

High compressive stresses due to external loading or prestressing in the concrete layer exposed to heating increase the probability of explosive spalling because they induce restraint and spalling occurs as a result of increasing stress as the concrete expands.

Normally explosive spalling is unlikely to occur for thick concrete members (EC2 1995, Schneider 1986) with low moisture content (Khoury 2000) under small load and the standard fire.

#### 4.2.9 Restraint

Restraint can hinder thermal expansion and give rise to thermal stresses (Hertz, 2003). Normal strength concrete showed higher levels of spalling when tested under restraint and the standard fire (Ali *et al* 2004). Restraint to structural members includes restraint to thermal expansion as well as thermal gradient. Restraint may be beneficial to a bowing beam under thermal gradient because the tension, experienced on the underside as a result of bending under imposed loading, is reduced by the beam expanding against restraints, closing any tension cracks (see Figure 2).

A restrained column exposed on 4 sides will attract more compression as it tries to expand resulting in stress induced spalling.

A wall will generally experience fire on one side only therefore will bow towards the fire if it is restrained around its edges.

From a practical point of view, all structural members can be regarded as being restrained at some level by adjacent cold structure. A slab or beam with free ends in a standard furnace test are the only elements, which could be considered to be unrestrained.

For this project it is assumed that all structural elements in a real buildings are restrained.

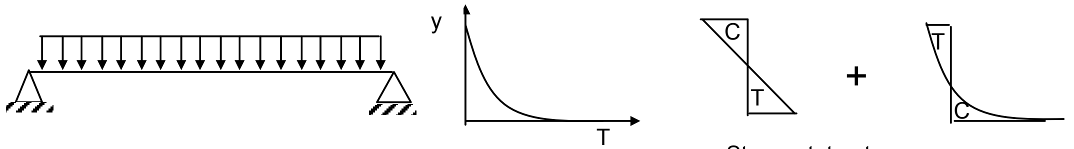



**Figure 2** Effect of a beam in bending exposed to a thermal gradient T,y (C=compression, T=tension)

#### 4.2.10 Thermal expansion

The expansion of a concrete gives a measure of its likelihood to spall. Concrete that has its thermal expansion restrained is more likely to spall. Consequently, concrete with low thermal expansion reduces the thermal stresses developed in a fire, therefore increases its spalling resistance. Thermal expansion of concrete increases with increasing temperature and therefore increases as the fire temperature increases.

Siliceous aggregate has higher thermal expansion than calcareous aggregate concrete, therefore is more susceptible to spalling than calcareous aggregates.

#### 4.2.11 Reinforcement

The presence of reinforcement in concrete will generally improve the spalling resistance of a concrete section because it halts or delays the development of spalling at the line of the reinforcement. Meyers Ottens (1977) believes that differential expansion of reinforcement and the surrounding concrete causes cracking and contributes to spalling. There is no evidence from other work to prove this conclusion. Moreover the thermal expansion coefficient of normal weight concrete and steel is of the same order ($\sim 10\times10^{-6}$). Spalling as a result of cracking is only likely to be the case if % reinforcement is high and densely packed in which case cracks may develop in the concrete at ambient because the concrete lacks continuity around the rebar. Spalling as a result of cracking is generally not associated with explosive spalling.

##### 4.2.11.1 Cover

For normal strength concrete, explosive spalling can often be restricted to the unreinforced part of the section and usually does not proceed beyond a reinforcing layer. Therefore it is believed that the greater the depth of cover, the greater the risk of spalling (Newman and Choo 2003). Standard fire tests (CIRIA 1987) have shown that spalling of limestone aggregate concrete was not observed for covers of up to 50mm within 2 hours of a standard fire. Spalling in gravel aggregate concrete ribs with covers to the main reinforcement of 35mm or less is not serious for up to two hours in a standard fire test. Significant spalling may occur with increased covers.

However BS 8110 Part 2 recommends that additional spalling measures should be taken for cover thickness greater than 40mm for NWC exposed to the standard fire.

#### 4.2.12 Fibres

Tests (Shuttleworth 1997, Lennon 2000, Both 2000) have shown that adding polypropylene fibres to the concrete mix is an effective method of reducing explosive spalling. Under relatively low temperatures, the polypropylene fibres melt, leaving a randomly orientated net of channels inside the concrete which help the high pressure vapour to escape and relieve the pressure inside the concrete, thus avoiding explosions.

Polypropylene fibres are usually used in high strength concrete to improve its permeability. For normal strength concrete, they are rarely used (Shuttleworth 1997, Kodur 1999, Khoury 2000). However this is probably because the concept of spalling is not explicitly considered as the norm in design.

Adding steel fibres in concrete has no obvious effect on improving the spalling resistance of concrete (Shuttleworth 1997).

#### 4.2.13 Density

The density of a specific concrete depends upon the aggregate used and the water/cement ratio.

High strength concrete is densified by the addition of silica fume and as a result has very low water/cement ratio and permeability, therefore this increases the risk of spalling.

There is no evidence in the literature to suggest that variations in the density of normal weight, ordinary strength concrete has an effect on spalling.

#### 4.2.14 Conductivity

High thermal conductivity results in higher concrete temperatures, therefore it can be assumed that it increases the spalling risk. Conductivity increases with an increase in moisture content which in turn increases the susceptibility of concrete to spalling.

#### 4.2.15 Specific heat

There is no information about the effect of specific heat on spalling in the published literature.

Table 3 is a summary of Section 4.2.

### 4.3 Influence of each variable on spalling

Researchers have mixed conclusions about the most critical factors which define spalling. This is to be expected given the number of variables involved and their interdependency. Table 4 is a summary of key factors as suggested by various researchers. Each factor is either related to moisture and pore pressures or to stress.

In general there is a split in thinking between those who believe that moisture content is the dominant factor and those who consider loading and thermal stress as a result of thermal expansion to be the dominant factor.

**Table 3** Factors affecting spalling

| Factor | Condition to increase spalling | Evidence in literature | Conflicting evidence in literature |
|---|---|---|---|
| Moisture content | High moisture content | <3% by weight then spalling unlikely (BS8110-2 1985, Khoury 2000, Newman and Choo 2003, Hertz 2003, Lennon 2004, CIRIA 1984) | Spalling has been observed in some limited instances at low moisture contents (Shuttleworth 1997) |
| Water/cement ratio (permeability, porosity) | Low w/c | Low w/c cause spalling, but no specific value is given in the literature (Khoury 2000, Newman and Choo 2003) | |
| Heating condition | Rapid heating e.g. hydrocarbon fire<br>Fire exposure on > 1 side | Rate of heating has a significant effect on the amount of spalling (Schneider 1986, Marsh 2002, Newman and Choo 2003, Anderberg 1997, CIRIA 1984)<br>Spalling is more likely if fire exposure is on more than one side (Schneider 1986, Lennon 2000, CIRIA 1984) | |
| Aggregate | Calcareous – low spalling<br>Siliceous – high spalling | Spalling less likely if a limestone aggregate is used. (Newman and Choo 2003, Kodur 1999)<br>Flint and river gravel increase spalling risk (Schneider 1986, Khoury 2000, Lennon 2000 ) | Limestone concretes do not always behave better. CTRL tests show no significant difference in spalling between limestone and granite concrete (Both 2000) |
| Test condition | Sealed (water cannot escape) – low spalling<br>Unsealed (fire case) – high spalling | Sealed conditions limit spalling (Huang *et al* 1991) | Unsealed conditions are better for spalling resistance (Khoury 2000) |
| Concrete strength | High strength | >55Mpa can be considered high strength and therefore a higher risk for spalling (Kodur 1999) | Design strengths are often exceeded on site. The mean strength may be up to 20% greater. 95% of results must be greater than the design strength. |
| Section size | Less than 200mm thick | If section is thin then water escapes from unexposed face. If section is thick (>200mm) then spalling is less likely. Most susceptible sections are those in the mid-range between thin and thick. (EC2 1995, CIRIA 1984) | |

| Factor | Condition to increase spalling | Evidence in literature | Conflicting evidence in literature |
|---|---|---|---|
| Applied Load | High compressive stress | High compressive strength in the concrete layer exposed to fire increase the probability of spalling (EC2 1995, Schneider 1986, Khoury 2000, CIRIA) | Bending of a beam may improve spalling resistance because the beam is in tension on its underside and thermal expansion as a result of fire will reduce tension and associated cracking.. |
| Restraint | Restraint | Normal strength concrete showed higher levels of spalling when tested under restraint and the standard fire (Hertz 2003, Ali *et al* 2004) | |
| Thermal expansion | High expansion coefficient | High thermal expansion increases the risk of spalling. | |
| Reinforcement | Steel in concrete with low thermal expansion | Reinforcement will generally halt spalling or at least delay it beyond the line of rebar. | Differential expansion between steel and concrete can promote spalling (Meyer-Ottens 1977) |
| Fibres | No polypropylene fibres | Polypropylene fibres (normally in HSC) significantly reduce or prevents spalling (Khoury 2000, Marsh 2002, Kodur 1999, Lennon 2000) | Steel fibre used to improve the tensile capacity of concrete has no obvious effect on spalling (Both 2000) |
| Density | Density is related to permeability and porosity. If these are low spalling is likely. | Silica fume used in high strength concrete decreases the permeability and increases the density. This leads to high spalling (Marsh 2002).<br>The density range of NWC does not vary greatly therefore does not influence spalling of NWC. | |
| Conductivity | High conductivity results in faster heating of the concrete section thus more spalling | Conductivity is greater if moisture content is higher (SINTEF 1988). If moisture content is high then spalling is more likely. | |
| Specific heat | | No information available | |

**Table 4** The key factor affecting spalling - Stress or moisture content

| Researcher | Main factor | Secondary factor |
|---|---|---|
| Saito (1965) | Initial load + restraint to expansion + stress caused by frictional resistance in concrete | Vapour pressure |
| Harmathy (1965) | Moisture clog | |
| Meyer-Ottens (1977) | Vapour pressure enhanced by frictional resistance in concrete + initial load + restraint to expansion | Initial load + restraint to expansion + frictional resistance in concrete, reinforcement expansion |
| Sertmehmetoglu (1977) | Moisture clog +internal cracks | Initial load |
| Akhtaruzzaman and Sullivan (1970) | Vapour pressure | |
| Gustaferro (1966) | Vapour pressure | Aggregate expansion |
| Copier (1977) | Vapour pressure + initial load | |

Having considered the findings of the literature review and the overview in Tables 3 and 4 we are taking the following views as to what we will include and note, for creating the risk categories as follows:

- The primary cause of spalling in concrete is moisture and associated pore pressures as moisture is heated in the concrete matrix during a fire.
- Moisture > 3% by weight is assumed to cause spalling.
- Moisture will be given a higher weighting in the risk categories defined in Section 5.2.
- Heating rate is a critical factor on the rate of spalling of concrete. This is related to moisture in that a rapid rate of heating causes a rapid build up in pore pressure and explosive spalling in the early stages of a fire.
- Stress induced spalling as a result of loading and restraint to thermal expansion is also an important factor although it is not as well defined as moisture. This is primarily because of the many variables which affect stress induced spalling including initial loading, end restraint conditions, magnitude of thermal expansion coefficient, section thickness, magnitude of fire temperature. Each variable contributing to stress induced spalling will be considered but weighted to lesser extent than moisture in the risk categories.
- All elements of structure in a building are restrained to some degree by surrounding structure. An unrestrained section only exists in a standard furnace. This will be captured by the spalling categories proposed.

The presence of reinforcement will be considered to promote spalling resistance when defining the risk categories.

# 5 Defining spalling risk categories

## 5.1 Overview

Spalling can be modelled explicitly using state of the art thermo-hydro-mechanical modelling techniques, which aim to consider all variables that lead to spalling including the build up of pore pressures as moisture evaporates from the concrete in a fire. The individual components of the micro structure of the concrete material are all represented in this type of modelling therefore it is very detailed. This level of accuracy is still firmly in the research domain and still requires significant validation. Due to the level of uncertainty still associated with this explicit approach it has therefore not been proposed for use on this project.

The alternative approach as proposed within Work Package 1 and 2, is instead to determine risk categories for spalling, based on the significant factors and available test data as follows.

**Work Package 2**

*Based on the results of work package 1 the range of concretes expected to be used on a nuclear site for enclosures will be categorised into a small number of spalling risk groups (high, medium and low). The groups are expected to be categorised by aggregate type, % moisture content, thermal expansion and concrete strength.*

*An estimated thickness of spalling will be assigned to each risk group based on conservative assumptions about the data from work package 1.*

*The risk groups will be defined in the database.*

After the detailed literature review now completed for Work Package 1 however, it has been concluded that there has been much less research on spalling of ordinary-strength normal-weight concrete in response to a hydrocarbon fire, which is the scenario to be considered in this project, than on spalling of normal weight concrete in a standard fire or high strength concrete in a hydrocarbon fire.

This is significant here as the concrete required for assessment by the HSE falls under this less researched category.

Therefore, there has been a slight change to the brief and five categories of spalling are proposed encompassing all the available test data presented in the data base. It can then be determined under what category the HSE directed concrete types requiring assessment, fall.

Additional factors affecting spalling not identified by the brief have also been considered in Work Package 2 these include section thickness, loading, presence of reinforcement and the number of sides of the concrete section exposed to fire.

Many publications and researchers have listed the key variables that are understood to influence each type of spalling, and in particular explosive spalling. In general there is a cut off for each variable at which spalling is assumed to be more likely. E.g. 3% by weight is the cut-off at which moisture is assumed to cause spalling of concrete. These are already listed in Table 3 and described in Section 4 of this report and will be used to assign values of risk to each variable affecting spalling. The available test data data will then be used to assign a quantity of spalling to different risk categories of concrete.

The HSE concretes will then be assessed on the basis of the created table, and assigned a risk category and associated spalling rate, for the purposes of the analysis required in the later Work Packages.

## 5.2 Definition of the risk associated with each individual variable known to affect spalling – assigning risk factors

In order to sort different concrete types into categories each variable known to influence spalling of concrete was split into an upper and lower bound and a "risk" value assigned to each (see Table 5). A value of 1 represents the lower bound of a variable, i.e. it is unlikely to affect spalling. A value of 3 is applied to the upper bound of those variables that are believed to have a medium effect on spalling and a value of 5 to those that have a high effect e.g. moisture above 3% by weight.

The risk values of 1, 3 and 5 represent an approximating scale in order to characterise the concrete at the level of knowledge which the research allows. In each case research indicates that the characteristic can affect spalling and the values allow us to distinguish between the characteristic which has less or more of this effect.

Evidence in the literature has not enabled us to distinguish between the relative importance of reinforcement, aggregate type, cover, section size, number of sides exposed, restraint or initial loading on spalling. Consequently they have all been assigned the same values either 1 where the characteristic is at the level which is known to relatively give better performance or 3 where it is known to give relatively worse performance.

The literature and test data have shown that the presence of moisture and the rate of heating have a more significant impact than the reinforcement, aggregate etc. Therefore these variables have been assigned a slightly higher weighting equal to 5 when the heating rate is equivalent to the hydrocarbon fire or the moisture is greater than 3% by weight.

Spalling of high strength concrete in a standard hydrocarbon fire is difficult to quantify. Therefore, for the purposes of this project it is assumed that high strength concrete is never less than Category D when exposed to a hydrocarbon fire. This is a simplistic approach but is required for completeness and to put the risk categories in perspective.

The value taken as the cut off between an upper and lower bound of a particular variable is based on the findings reported in Section 4 of this report, and as presented in the data base; the following limitations should be noted;

- In general spalling is not expected in concrete with a moisture content below 3% but there have been exceptions noted in the test data reviewed here. This will be discussed with the HSE. For the purposes of this work it is assumed that 3% is the critical value for spalling because a greater number of researchers have agreed upon this value.
- A design strength 55MPa is assumed to be the limit between ordinary strength and high strength concrete. Note a higher level of strength may occur on site. Indeed 95 % of the samples tested should be greater than the design strength. However, concrete mixed on site that has a higher strength than its design strength is not the same as high performance concrete with silica fume and very low permeability, which is very susceptible to spalling.
- Limestone aggregate concretes have shown increased spalling resistance compared to siliceous concrete but there are exceptions noted in the test data reviewed here. For the purposes of this exercise the exceptions have been ignored.
- The literature review has shown that moisture and heating rate have a significant effect on spalling whereas all other variables, which are known to have an effect on spalling, are generally considered to be secondary. This same approach has been adopted when developing the risk factors.

**Table 5** Risk factors for each variable known to affect spalling of concrete

| | RISK |
|---|---|
| Design Strength >55Mpa | Not quantified |
| Design Strength ≤55Mpa | 1 |
| Hydrocarbon fire | 5 |
| Standard fire (BS 476) | 1 |
| Moisture content >3% | 5 |
| Moisture content ≤3% | 1 |
| No Reinforcement | 3 |
| Reinforcement included | 1 |
| Cover ≥ 40mm | 3 |
| Cover <40mm | 1 |
| Siliceous aggregate | 3 |
| Calcareous aggregate | 1 |
| No. of sides exposed >1 | 3 |
| No. of sides exposed = 1 | 1 |
| Section size <200mm | 3 |
| Section size ≥ 200mm | 1 |
| Restrained | 3 |
| Unrestrained | 1 |
| Thermal expansion ≥ 10 x $10e^{-6}$ | 3 |
| Thermal expansion < 10 x 10 $e^{-6}$ | 1 |
| Loaded in compression | 3 |
| Unloaded | 1 |

## 5.3 Definition of the total risk of spalling associated with a particular concrete – assigning risk categories

In order to arrive at a total risk of spalling for a particular concrete it is proposed that the risk associated with each variable (in Table 5) can be added together and then further categorised.

Five generic categories (A-E) are proposed as set out in Table 6 and associated with a "total risk" value. A quantity of spalling associated with that risk category has then been defined by evidence from fire tests. This is described in Section 5.4 of this report.

To arrive at a "total risk" value for a particular concrete, all of the relevant individual "risk" values from Table 5 are added together. The value of "total risk" will then fit into the range for each of the categories in Table 6.

For example:

OSC: hydrocarbon fire, 2% moisture, no rebar, cover > 40mm, siliceous aggregate, sides exposed =1, section size >200m, restrained, low thermal expansion, unloaded:

= 1+5+1+3+3+3+1+1+3+1 + 1=23 ⇨ Risk Category C

**Table 6** Spalling categories and associated spalling levels (*key factors = properties of the concrete or the boundary conditions that are known to promote spalling e.g. aggregate type, section thickness etc)

| Category | Risk of spalling | Value of Total Risk | Key factors |
|---|---|---|---|
| A | Very low | ≤11 | Ordinary strength, NWC, Unloaded, Unrestrained, Standard fire exposure, Reinforced, moisture <3%, one side exposure |
| B | Low | 12-20 | Ordinary strength, NWC, restrained, Standard fire exposure<br>Significant number of key variables* likely to promote spalling |
| C | Med | 21-28 | Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure<br>Small number of key variables* likely to promote spalling |
| D | High | 29-37 | Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure<br>Significant number of key variables* likely to promote spalling |
| E | Very high | >37 | High strength (Design strength >55Mpa), standard hydrocarbon fire exposure. |

## 5.4 Quantification of the level of spalling for each risk category

### 5.4.1 Category A - Very Low risk

Spalling category A is associated with unrestrained, unloaded elements tested in a standard furnace where test evidence has shown that spalling is unlikely or very limited. This category is not representative of concrete elements in real buildings but is an idealised test condition. In addition a moisture content of < 3% by weight of concrete is assumed in these tests, according to the literature.

The value of "total risk" associated with this very low risk category is the sum of all the low values in Table 5.

Category A is a lower bound to the generic spalling categories defined for this project and is presented to allow comparison with the spalling rates in other categories under which the concrete required for assessment by the HSE falls.

For Category A therefore the quantity of spalling assumed is 0mm/min.

This is not real for design but acts as a good reference point for comparison.

### 5.4.2 Category B - Low risk

Spalling category B also assumes the standard fire exposure but with several key variables such as moisture content now contributing to spalling. In this case evidence from standard furnace testing suggests the cover to the concrete would spall only (Lennon 2004).

For Category B therefore the quantity of spalling assumed is to equal the cover to reinforcement.

#### 5.4.3 Category C - Medium risk

The spalling rates in this category have been defined by considering test data specific to normal weight, ordinary strength concrete in hydrocarbon fires which is the scenario to be considered as part of this project. However it should be noted that the design fire to be produced by the HSE and analysed in Work package 5 is not the standard hydrocarbon fire. Provided the rate of heating is similar to or less than in the standard hydrocarbon fire the spalling rate will be conservative for the design fire. If not these spalling rates may need to be re-visited.

The most comprehensive research into spalling levels in ordinary strength concrete elements exposed to a standard hydrocarbon fire is based on the results of tests by SINTEF and assessment of these by Arup (SINTEF 1988, Arup 1993). The tests conducted for the offshore industry , considered normal weight pre-stressed concrete sections, unrestrained and unloaded exposed to a standard hydrocarbon fire on one side. Note although the sections were unloaded the pre-stress has a similar effect on the section as initial loading.

The spalling rate for pre-stressed normal density concrete in a standard hydrocarbon fire was quantified in the literature as 3mm/min.

The value of 3mm/min was also derived by Arup (1993) for normal density concrete exposed to the hydrocarbon fire. They assumed that when a 10mm layer of concrete reached 360°C it would spall off and expose the next 10mm, which in turn would also spall. Using this method, 75mm of concrete was shown to start spalling after 5 minutes and have totally spalled after 19minutes in a standard hydrocarbon fire. This is comparable to 75 x 3mm/min = 25 minutes.

#### 5.4.4 Category D - High risk

The spalling rate in this category was difficult to define because spalling rates have not been recorded for normal weight, ordinary strength concrete where many factors contributing to spalling are unfavourable. It is reasonable to assume that the rate of spalling would be greater than 3mm/min as defined for Category C.

The only significant work looking at spalling rates in concretes which have a high susceptibility to spalling is fire tests on relatively wet LWC used in the offshore industry also by SINTEF (SINTEF 1988). LWC used in the offshore sector is characterized by high strength, high moisture and low permeability. The tests considered lightweight pre-stressed concrete sections unrestrained, unloaded exposed to a standard hydrocarbon fire on one side. The design strength of the concrete specimen was about 60N/mm$^2$.

The LWC SINTEF tests showed spalling of the concrete started earlier than in the NWC tests. A spalling depth of 180mm was reached in 25minutes. This is because of the poor tensile strength and low permeability of the LWC and higher temperature gradients at the outer surfaces.

The conclusions of these tests derived a spalling rate of 7mm/min for pre-stressed LWC.

In this project it has been decided to use this value for NWC in a hydrocarbon fire where a significant number of the key factors in the concrete enclosure design like moisture adversely affects spalling. This is because there is no data available for spalling of normal weight concrete in conditions where many variables contribute to spalling. However, this is a robust approach because relatively wet LWC in a standard hydrocarbon fire has been shown to spall severely.

It is likely that a spalling rate somewhere between 3-7mm/min is more suitable for Category D type concretes but this is limited by available test data and 7mm/min is proposed at this stage because any other value is difficult to justify.

#### 5.4.5 Category E _Very High Risk

The level of spalling in Category E is unquantifiable because it is associated with high strength concrete in a standard hydrocarbon fire test. Fire tests have shown that severe spalling can occur in this scenario and the only method of preventing it is to include polypropylene fibres in the concrete mix.

Category E has been created as a known upper bound to the generic spalling categories defined for this project.  It is only presented for comparison with the spalling rates in other categories in which the concrete required for assessment by the HSE will fall.

Therefore the quanity of spalling assumed for category E is “unquantifiable”.

**Table 7** : Final risk categories with associated spalling quantification

| Category | Risk of spalling | Value of Total Risk | Key factors | Spalling level |
|---|---|---|---|---|
| A | Very low | ≤11 | Ordinary strength, NWC, Unloaded, Unrestrained, Standard fire exposure, Reinforced, moisture <3%, one side exposure | Zero or minimal |
| B | Low | 12-20 | Ordinary strength, NWC, restrained, Standard fire exposure<br><br>Significant number of key variables* likely to promote spalling | Up to the level of the reinforcement |
| C | Med | 21-28 | Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure<br><br>:Small number of key variables* likely to promote spalling | 3mm/min |
| D | High | 29-37 | Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure<br><br>Significant number of key variables* likely to promote spalling | 7mm/min |
| E | Very high | >37 | High strength (Design strength >55Mpa), standard hydrocarbon fire exposure. | Unquantifiable |

### 5.5 Limitations on the use of the risk categories

The risk factors and risk categories derived as part of this project in Tables 5, 6 and 7 respectively should only be used in the assessment of normal weight, ordinary strength concrete enclosures as defined by the brief.

Lightweight concretes are not considered and the spalling risk associated with high strength concretes in a standard hydrocarbon fire are presented in a simplistic manner for comparison with the other categories only.

High strength concrete typically contains silica fume to increase the strength by reducing the porosity of the concrete. High strength sections designed in this manner are typically thin in section therefore any spalling has a significant impact. For this reason the addition of polypropylene fibres has become common place in high strength concrete.

High strength concrete without the addition of silica fume is also possible. The extent to which this type of section spalls is probably less than with silica fume but is still high.

If the HSE were to rigorously assess high strength concrete enclosures (not currently part of this brief) a more detailed investigation of the high strength category concretes would need to be conducted to adapt the risk categories and associated spalling rates accordingly.

The risk categories also assume a standard BS476 fire or standard hydrocarbon fire. If the design fire produced by the HSE is significantly different from the standard hydrocarbon fire the categories may have to be revisited.

# 6 Conclusions

- Conductivity, specific heat and density of concrete and its constituent materials is well defined and readily documented in the literature. The ranges recorded in the database and their effect on the temperature attained by concrete in a standard hydrocarbon fire shall be investigated in work packages 3 and 4 of this project.
- The literature review has shown that spalling is considered to be caused primarily by moisture and a build up of vapour pressures in the concrete matrix as fire causes water migration and phase change from water to steam.
- Spalling as a result of stress induced by loading and restrained thermal expansion is also significant but for the purposes of categorising risk in this project has been considered secondary to moisture, based on the literature.
- There is limited test information on normal weight ordinary strength concrete in response to the standard hydrocarbon fire, which is the scenario of concern. Note the HSE design fire may significantly different from the standard hydrocarbon fire in which case the relevance of this data will have to be checked.
- Consequently five categories of spalling have been proposed encompassing the available test data. It can then be determined under what category the HSE directed concrete types requiring assessment, fall. Note these are based on the standard hydrocarbon fire. This is a change to the original brief in which three categories were proposed (low, med, high) for ordinary strength, normal weight concrete only. This allows a comparison between extremes of spalling risk and gives perspective to the ratings associated with normal weight, ordinary strength concretes in response to the hydrocarbon fire.
- Additional factors affecting spalling not identified by the original brief have also been considered in work package 2, due to the literature review. These include section thickness, loading, presence of reinforcement and the number of sides of the concrete section exposed to fire. This allowed a more refined development of the risk categories.
- The most significant work on spalling rates of ordinary strength, normal weight concrete in the standard hydrocarbon fire has been carried out by Arup on the basis of tests by SINTEF. This has therefore been used in defining spalling rates for two of the risk categories in this project [medium and high risk].
- There are a number of conclusions made in the literature about the effect of individual variables (e.g. moisture, thermal expansion). As a result of the complexities

associated with concrete spalling and the interdependency of the associated variables there are also often conflicting view points in another article or report.

- The spalling categories assigned to different concrete types in this report are considered to be conservative based on the information and test data available in the public domain.
- The spalling categories have been validated by comparison with available test data and will continue to be validated as more data becomes available in the subsequent stages of this project.
- Lightweight concretes are not considered in the risk categories.
- The spalling risk associated with high strength concretes in the standard hydrocarbon fire which is the output from this Work Package presented here, are presented in a simplistic manner for comparison with the other risk categories, and as an upper bound only.
- The risk categories and defined spalling quantities associated with each, will allow the inclusion of spalling in the heat transfer analysis of the HSE enclosures.
- The risk categories also assume a standard fire (BS 476) or standard hydrocarbon fire. If the design fire produced by the HSE is significantly different from the standard hydrocarbon fire the categories may have to be revisited.
- Provided the rate of heating in the design fire is similar to or less than in the standard hydrocarbon fire the spalling rates specified for each risk category should be conservative for the design fire.

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Appendix A

# Hierarchy of folders and files in database

# A1 Hierarchy of folders and files in Database

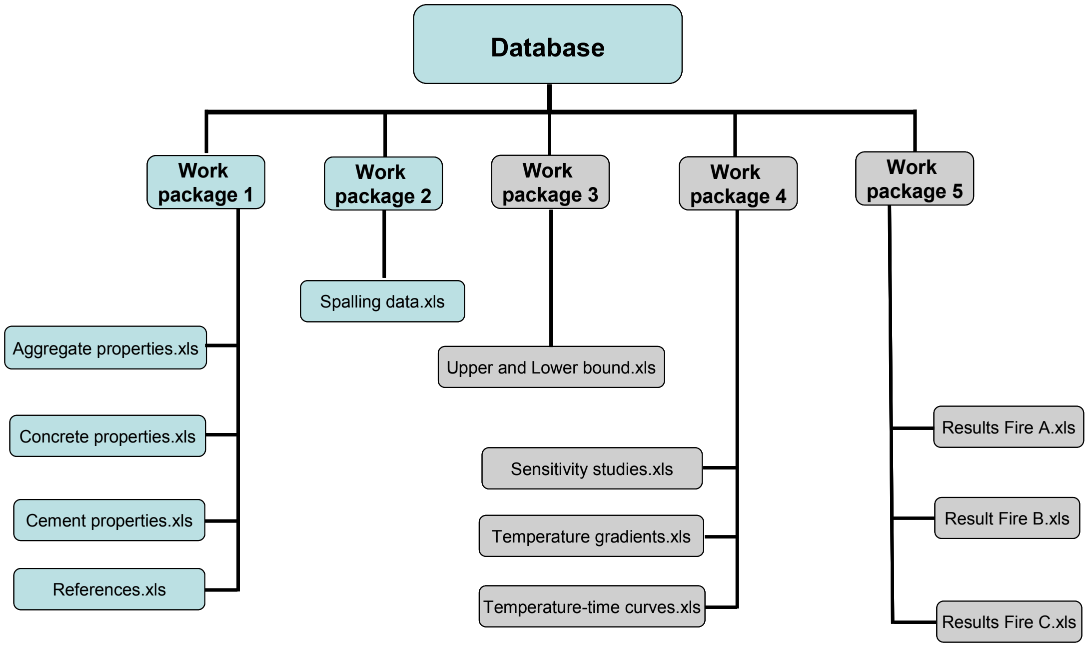


**Figure A1** Flowchart showing hierarchy of folders and files in the database to be read in conjunction with Table A1 which describes the content of each excel file.

| File name | Contents |
|---|---|
| Aggregate properties.xls | Values of conductivity, thermal expansion, specific heat, strength, moisture content and density at various temperatures for various aggregates. |
| Concrete properties.xls | Values of conductivity, thermal expansion, specific heat, strength, moisture content and density at various temperatures for various concretes. |
| Cement properties.xls | Values of conductivity, thermal expansion, specific heat, strength, moisture content and density at various temperatures for cement. |
| References.xls | List of literature referenced by this project. |
| Spalling data.xls | Guidance on spalling in literature, record of spalling in past fire tests etc. |
| Upper and lower bound.xls | Results of Work Package 3 showing the temperature on the unexposed face of the wall for the upper and lower bound case. |
| Sensitivity studies.xls | Results of Work Package 4 showing the sensitivities of the temperature on the unexposed face of the wall to each variable affecting heat transfer. |
| Temperature gradients.xls | Results of Work Package 4 showing the sensitivities of the gradient through the wall to each variable affecting heat transfer. |
| Temperature-time curves.xls | Results of Work Package 4 showing the sensitivities of the temperature time curves at various depths in the wall to each variable affecting heat transfer. |
| Results Fire A.xls | Heat transfer results in the form of temperature-time curves at various depths through the walls for Fire A. |
| Result Fire B.xls | Heat transfer results in the form of temperature-time curves at various depths through the site specific wall for Fire B. |
| Results Fire C.xls | Heat transfer results in the form of temperature-time curves at various depths through the walls for Fire C. |

**Table A1** The content of each excel file listed in Figure A1