United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NIST Special Publication 919

International Workshop on Fire Performance of High-Strength Concrete, NIST, Gaithersburg, MD, February 13-14, 1997 Proceedings

Long T. Phan, Nicholas J. Carino, Dat Duthinh, and Edward Garboczi

B.3 Spalling Phenomena of HPC and OC

Y. Anderberg, FSD, Sweden

1. Swedish Research Project on HPC

In 1992, the Swedish research project on High Performance Concrete (HPC) started. It was financed jointly by government and industry. The research on fire performance of HPC is a part of that project and has been carried out by Fire Safety Design during a period of 5 years. The scope of work includes investigation concerning:

- tendencies to spall
- thermal properties
- mechanical properties

and developing:

- analytical behavior models
- structural models for mechanical behavior
- structural design models for practical use

2. Background

Fire-exposed HPC has a different tendency and feature of spalling compared with ordinary concrete (OC). Due to the compact structure of HPC, which makes it more difficult to transport vapour and moisture, very high vapour-pressure may occur close to the surface. This means that there is a greater risk that HPC spalls compared with ordinary concrete (OC).

In OC, the vapour can be transported much more easily to the surface and, likewise, the moisture towards the inner part. However the moisture concentration can at last be too large and explosive spalling of 20-40 mm concrete cover can occur.

Consequently it is of great importance to find different ways of decreasing the risk and tendency of spalling for HPC. One measure is to choose a concrete mix with various additives to improve the permeability and the pore structure. Another step is to ensure a sufficiently small relative humidity of the HPC in case of fire by allowing a continous hydration and self desiccation process to take place where the free water is transferred to chemically bound water with a volume decrease of 25%. Because spalling tendency is such an important property of HPC under fire the phenomenon must be understood properly.

2. Spalling as Phenomenon

When surface spalling of fire-exposed concrete structures occurs, smaller or greater parts disappear and the reinforcement cover might be gone, which leads to direct heating of the reinforcement and a rapid decrease of load-bearing capacity. Sometimes the spalling can be very comprehensive and cause an immediate failure of the structure. The spalling can be explosive or can be a calmer process.

The tendency for surface spalling is increased by:

- High moisture content
- Dense concrete (HPC)
- Compressive stress from external load and prestress
- Rapid temperature rise
- Considerable unsymmetrical temperature distribution
- Cross-section with thin sections
- High reinforcement concentration

Increase of air in OC is positive as far as spalling is concerned, but for HPC this is of no interest because it influences the strength negatively.

Three primary mechanisms can be identified which separately or in combination can cause surface spalling

- Vapour pressure
- Thermal stresses
- Structural transformation of aggregate

In most cases the vapour pressure is the most important primary mechanism. This is valid especially when the spalling is vast and occurs explosively. The third mechanism is limited to coarse aggregate only.

By heating moist concrete above the boiling point the free water of the material transforms into vapour as the temperature increases. If the material has small diffusivity, the transport of vapour is hindered and an over-pressure is attained. The size of this over-pressure is governed by the balance between the transportation and production of vapour. Spalling takes place if the vapour pressure - possibly in combination with thermal and statical stresses - causes tensile failure in the material.

By heating concrete, a simultaneous process of heat and moisture transport is initiated. The moisture is transported both in vapour and water phase. In the following, a qualitative description of the process is presented. The description is based on a pure one-dimensional case for HPC and OC, i.e., a concrete wall exposed uniformly to fire from one side.

The water is vapourized at the hot surface first, when the temperature reaches 100 °C. As the temperature rises, the vapour zone moves towards the inner part. In Fig 1 the situation is illustrated after a certain time for HPC as well as OC. Nearest the hot surface there is a dry zone, whose thickness increases faster for OC than for HPC. After that follows a narrow zone which is thinner for HPC where vapourization takes place, and inside is a zone where the moiture exists as free water. The vapour, which is created in the vapour zone is transported towards the hot surface but also in the opposite direction where it is cooled down and condenses to water. This means an increased moisture content just inside the vapour zone. The transport of vapour is mainly driven by over-pressure which is maximum at the front of vapourization.

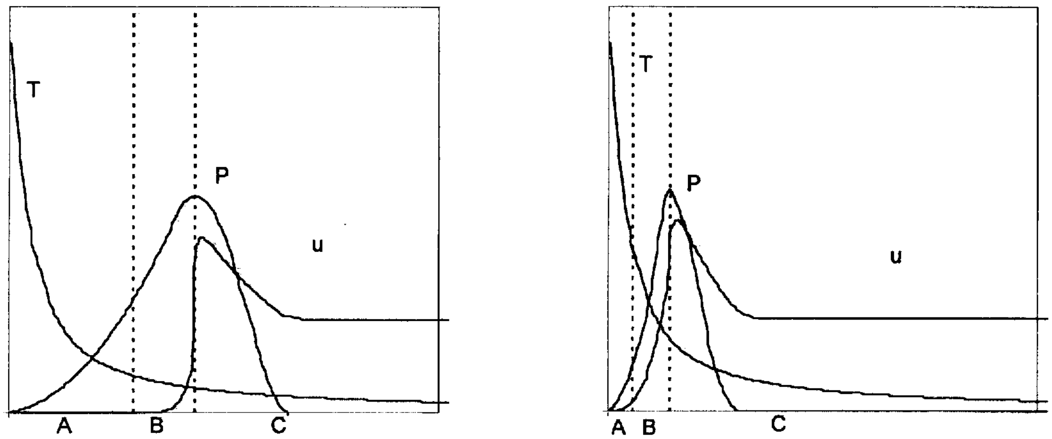
As the vapour front moves inwards, the distance to the hot surface increases, and a higher pressure is needed to lead the vapour away. At the same time the moisture content increases in the domain inside the vapour zone, which causes less vapour transport towards the cold side. Therefore the vapour pressure tends to increase at the vapour front as it moves inwards. However, the intensity of the heat flow decreases with increasing distance to the hot surface, which gives less vapour production. Furthermore, it can be assumed that the hydrodynamic resistance of the outer dry zone does not increase in proportion to its thickness. The temperature rises rapidly in this zone and the gas diffusivity of concrete increases strongly with the temperature. When the distance to the cold surface decreases, the water flow is facilitated in that direction.

When the vapour zone moves to a certain distance from the hot surface, a maximum vapour pressure is created, and at greater distances the pressure decreases again. This critical distance is much less for HPC, about 5-10 mm than for OC, about 20-40 mm. Whether the vapour pressure developed is sufficient to cause spalling depends not only on the amount of moisture, but also on rate of heating, permeability, porosity and pore distribution.

It has been observed from fire tests that spalling of HPC is characterized by a layer of about 5 mm of concrete falling off and after that a new vapour front buildup, which can create a new spalling of 5 mm, and in the end the total spalling can reach considerable depths.

This summary description is only valid for heated, moist concrete in idealized conditions. In practise these conditions can change. Creation of cracks in concrete will facilitate the vapour and moisture transport and reduce the tendency of spalling.

If the concrete wall is exposed to fire on both sides, the inner part of the section will contain further free water if the diffusivity is large enough (OC). This may cause a total collapse of OC. This phenomenon is not probable for HPC.

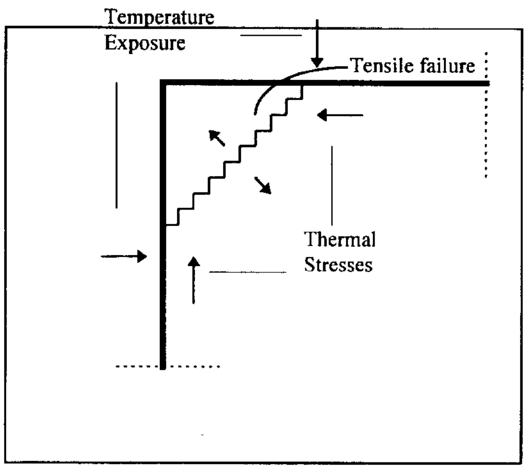


a) OC *b) HPC*

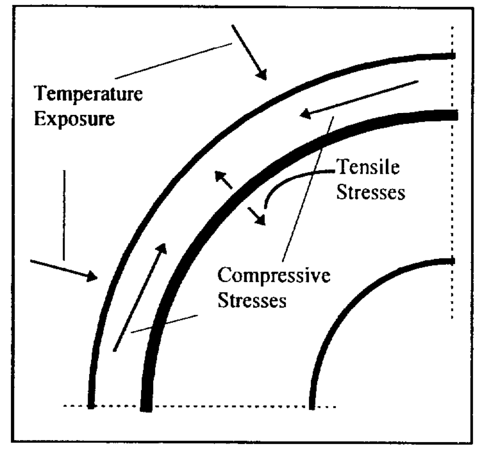
Fig 1. Schematic illustration of temperature- and moisture conditions at one-dimensional heating of moist OC and HPC
A: Dry concrete, B: Vapour zone, C: Moist concrete.
T: Temperature, P: Vapour pressure, u: Moisture content

4. Influence of Thermal Stresses on Spalling

Heating of concrete is characterized by a steep thermal gradient when exposed to fire due to low conductivity and high heat capacity. This produces thermal stresses, which generally are two- or three- dimensional. Consequently tensile stressses arise which can reach the tensile strength. These tensile stresses can sometimes alone or in superposition with pore pressure in one direction, cause spalling. In Fig 2 two different examples are shown where the thermal stresses alone may cause spalling. When the thermal compressive stresses in the hot outer layer are developed and meet each other in a corner, tensile stresses appear. If this tensile stress reaches the tensile strength, the triangular corner piece can spall off as indicated in Fig 2. The same problem occurs for a heated convex surface where radial tensile stresses develop.



a)



b)

Fig 2. Thermal stresses at a
a) corner
b) convex surface

5. Conclusions

If HPC, without any additives like polypropylene fibers and with a water binder ratio (w/b) less than about 0.28, is exposed to the standard fire exposure, ISO 834, it is characterized by a successive spalling of 5 - 10 mm thickness, and the longer the fire duration, the deeper the concrete spalls. Therefore the total spalling may lead to a disaster. External loading increases the risk of spalling. If the heating rate is less, the risk of spalling decreases. At the heating rate of 5 °C/min, the spalling tendency is very small.

The relative humidity (RH) as function of time decreases much faster for HPC than for OC. After 3 months of curing, the RH of HPC can be as low as 60%. Due to the continous hydration of the cement, the self desiccation effect seems to be advantageous.

In the Swedish investigation on HPC, it is found that the risk of spalling is low if w/b is greater than 0.32 and the RH is less than 75-80 %. At lower w/b values, polypropylene fibers (or similar) must always be added, but the relative humidity must, nevertheless, not exceed 80 %. The results are limited to one type of concrete mixture with granite aggregate. The limited number of tests means that the conclusion is not generally applicable to different kinds of HPC.

Current code requirements of minimal thickness of concrete slabs and walls made of OC are not valid for HPC.