Spalling Phenomena of HPC and OC

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1. Swedish Research Project on HPC

In 1992 the Swedish research project on High Performance Concrete (HPC) in general started which was financed jointly by the government and the 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 spalling
- thermal properties
- mechanical properties
-

and to develop

- analytical behaviour models
- structural models for mechanical behaviour
- 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 much easier be transported to the surface and 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 for HPC is such an important property at fire the phenomenon must be understood properly.

2. Spalling as phenomenon

When surface spalling of fire-exposed concrete structures occur smaller or greater parts disappear and the reinforcement cover is maybe 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 be a more calm process.

Increased tendency for surface spalling by

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

Increase of air in OC is positive as concerns spalling 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 single aggregate coarse.

By heating moist concrete above the boiling point the free water of the material transfers into vapour as the temperature increases. If the material has a 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 a concrete a simultaneous heat and moisture transport starts. 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 from one side.

The water is vapourized at the hot surface first, when the temperature has reached 100 °C. As the temperature rises, the vapour zone is moving 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 is increasing faster for OC than for HPC. After that follows a narrow zone which is less for HPC where vapourization takes place and inside this a zone where the moiture exists as free water. The vapour, which is created in the vapourzone is transported towards the hot surface but also in the opposite direction where it is cooled down and condensated to water. This means an increased moiture 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 is moving inwards the distance to the hot surface is increasing a higher pressure is needed to lead the vapour away. At the same time the moisture content is increasing in the domain inside the vapour zone which cause less vapour transport towards the cold side.

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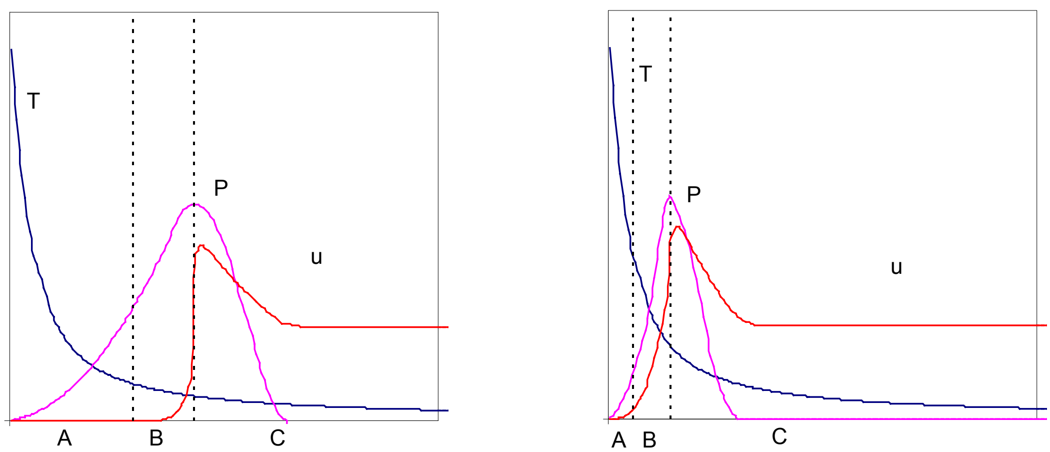
Therefore the vapour pressure tends to increase at the vapour front as it moves inwards. However the intensity of the heat flow is decreasing with increasing distance to the hot surface which give less vapour production. Furthermore it can be assumed that the hydrodynamic resistance of the outer dry zone is not increasing in proportion to its thickness. The temperature will soon be high in this zone and the gasdiffusivity of concrete is increasing strongly with the temperature. When the distance to the cold surface is dereasing the water flow is facilitated in that direction.

When the vapour zone is moved to a certain distance from the hot surface a maximum vapour pressure is created, at greater distance the pressure is decreasing again. This critical distance is much less for HPC, about 5-10 mm and for OC estimated to be 20-40 mm. If the vapour pressure developed is sufficient to cause spalling depends mainly 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 about 5 mm layer of concrete is falling off and after that a new vapour front is built up which can create a new spalling of 5 mm and in the end the total spalling can reach considerable depths.

This principal description is only valid of heated, moist concrete at idealised 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 Principal 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

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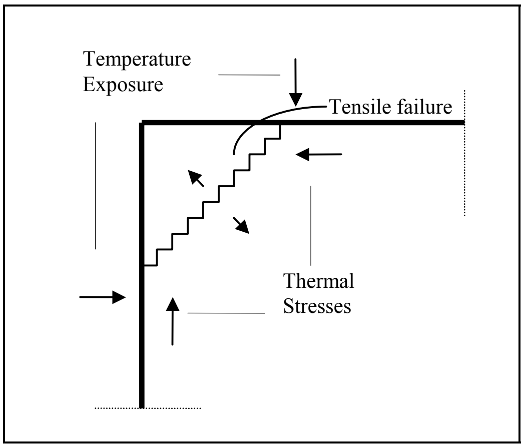
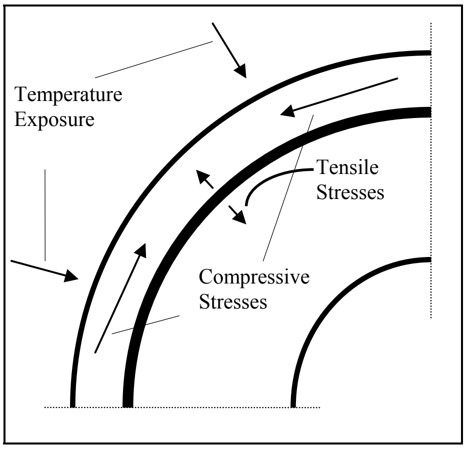
Heating of concrete is characterized by a steep thermal gradient when exposed to fire due to the low conductivity and high heat capacity. This renders thermal stresses which generally are two- or three- dimensional. Consequently tensile stressses arise which can reach the tensile strength. These tensile stresses can sometimes alone or in superposition of 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 reach the tensile strength the triangular corner piece can spall off as indicated in the Fig 2. The same problem occurs for a heated convex surface where radial tensile stresses develops.



a)



b)

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

5. Conclusions

If HPC, without any additives like polypropylene and with a water binder ratio (wbr) 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 fire duration the deeper it spalls. Therefore the total spalling may lead to a disaster. External loading increase the risk of spalling. If the heating rate is less the risk of spalling is decreasing. At the heating rate of 5 °C/ min the spalling tendency is very small.

The relative humidity (rh) as function of time is decreasing much faster for HPC compared with OC. Already after 3 months curing relative humidity of HPC can be as low as 60%. Due to the continous hydration of the cement the selfdesiccation effect seems to be advantageous.

In the Swedish investigation on HPC it is found that the risk of spalling is low if wbr is greater than 0.32 and the relative humidity is less than 75-80 %. At lower vbt values polypropylene fibres (or similar) must always be added but the relative humidity must

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never the less 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 by OC is not valid for HPC.

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