A method to inspect the risk of fire spalling of existing concrete members

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ABSTRACT: The risk of spalling induced by fire has been a main concern in the use of concrete. For decades, significant effort focussed on the nature of fire spalling of concrete. Research at ETH Zurich has shown that the permeability of concrete is a good indicator of the risk of fire spalling, as concrete with low permeability is more prone to explosive spalling. Based on test results, a practical method has been proposed to predict the risk of fire spalling. The effects from concrete strength grade, external loading and heating scenario are taken into account. For existing concrete members, the risk of fire spalling can be determined from non-destructive tests. The proposed spalling model and permeability model have been validated against test results, and some practical applications are reported.

1 INTRODUCTION

Concrete has been the most used construction material for many years due to its broad applicability and low cost. Due to a relatively high thermal capacity and low heat conductivity, the fire resistance of concrete members is usually good and the penetration of heat is slow. Improvements in concrete technology, including the use of silica fume, have led to new, dense concrete. Apart from increasing the strength, the use of silica fume is known to decrease the permeability of these concrete mixes, which has a beneficial effect on the durability of concrete members. However, these new dense concretes have been reported to be more prone to fire spalling, causing a severe loss of cross-section and thus bearing capacity under fire. The fire safety issue of modern concrete members, e.g. prefabricated elements, high-strength concrete (HPC) and self-compacting concrete (SCC) members, has become a major concern in the use of concrete (Jansson (2013) and Malhotra (1984)).

In practice, much effort has been focussed on minimizing the risk of concrete spalling in fire. Since 2014, in Switzerland polypropylene fibers (PP-fibers) are added to dense concrete to reduce the risk of fire spalling. Also for existing concrete members without protective measures, spalling risk assessment is required to meet fire safety demands. To develop reliable assessment methods and design models, experiments on spalling of various concrete mixtures have been carried out at ETH Zurich (Klingsch et al (2013)). Based on the test results, a spalling model and a permeability model have been proposed to assess the risk of spalling induced by fire (Lu et al (2015)). The risk of fire spalling can be estimated based on data from non-destructive tests. Details of the method and some applications are presented in this paper.

2 ESTIMATION OF THE RISK OF FIRE SPALLING

Referring to fire spalling of concrete, many factors have been found related to the occurrence of the phenomenon, e.g. permeability, moisture content, fire scenario, external load, etc. (Klingsch et al (2013)). Mechanisms of fire spalling based on pore pressure or thermal stress have been proposed (Jasson (2013)). While these individual theories based on one of the two mechanisms could usually explain some observations in tests, they fail to consider the equally important role of the other mechanism. To date, academics generally believe that fire spalling is induced by the combined effects from both pore pressure and thermal stress. With this hypothesis, many of the contradictory characteristics of spalling that have been observed by researchers over recent years can be comprehensively explained.

2.1 Spalling model

The spalling model is an energy based method proposed by Zhukov (1976), using the elastic theory to qualify the total strain from pore pressure, thermal stresses and external loads. In this way, the thermo-hydro and thermo-mechanical effects are combined to predict spalling. Equation (1) represents the strain energy density w_p. When w_p exceeds the critical concrete spalling energy $w_{spalling}$ described by equation (2), spalling is said to occur. In equation (1), the strain ε_p depends on the pore pressure and thermal stresses in the *y* and *z* directions.

$$w_P = \frac{1}{2} a \sigma_P \varepsilon_P \tag{1}$$

$$w_{spalling} = \frac{1}{2} f_{t,T} \frac{f_{t,T}}{E} \tag{2}$$

$$\varepsilon_P = \frac{1}{E}\left[\alpha\sigma_P - v(\sigma_{thermal\_y} + \sigma_{thermal\_z} + 2\alpha\sigma_P)\right] \tag{3}$$

where, $f_{t,T}$ is the tensile strength of concrete at temperature T, σ_p is the pore pressure, α is Biot's coefficient for spalling defining the fraction of pore pressure transferred to the total stress, $\sigma_{thermal}$ are the thermal stresses perpendicular to the spalling direction, v is Poisson's Ratio for concrete and E is the Young's modulus. The thermal stresses are self-equilibrating and calculated based on linear coefficient of thermal expansion.

When the strain energy density w_p exceeds the concrete spalling energy, i.e. $w_p \geq w_{spalling}$, spalling is predicted. To compare the spalling stress to temperature dependent tensile strength, a simplified combined spalling stress from equations (1-3) is used:

$$\sigma_{spalling} = \sqrt{(1-2v)a^2\sigma_P^2 - v(\sigma_{thermal\_y} + \sigma_{thermal\_z})a\sigma_P} \geq f_{t,T} \tag{4}$$

Using this spalling model, spalling can be predicted considering pore pressure, thermal stresses and heating scenario. For the example shown in Figure 1, spalling was predicted after 25 minutes of ISO fire exposure, when the spalling stress $\sigma_{spalling}$ exceeds the temperature dependent tensile strength.

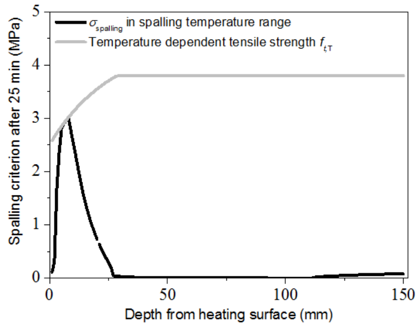

Figure 1. Spalling stress and $f_{t,T}$.

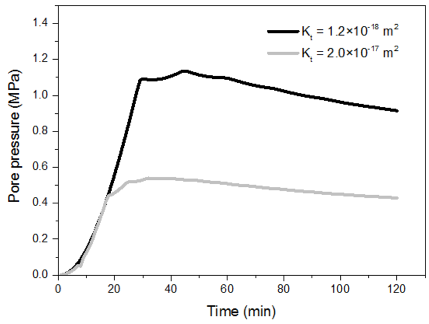

Figure 2. Pore pressure in a concrete slab with different permeability at 5 mm depth.

2.2 *Pore pressure and permeability*

The increase of pore pressure in concrete is a key factor regarding fire spalling of concrete. According to equation (4), the spalling stress $\sigma_{spalling}$ increases with the pore pressure during heating, and as a result the risk of spalling increases as well.

To simulate the development of pore pressure in concrete, a thermo-hydro model based on the considerations by Dwaikat et al (2009), has been applied in the spalling model. The permeability of concrete has been found to have significant effect on pore pressure in concrete. Figure 2 shows the pore pressure predictions of concrete with various permeability. Lower permeability results in higher pore pressure and thus higher spalling risk. The parameter study has shown that permeability is the key factor in estimating the fire spalling of concrete (Lu et al, (2015)).

However, concrete permeability is influenced by moisture content (Jacobs, (1994), Lu et al (2016)), decreasing with increase in moisture content. Concrete permeability must be measured considering the moisture content. With this data, the spalling risk of existing concrete members can be accurately estimated using the proposed spalling model.

3 PERMEABILITY MEASUREMENT AND PERMEABILITY MODEL

To study concrete permeability, various tests have been carried out at ETH Zurich (Lu et al, (2016)). Based on the test results, a permeability model has been proposed to calculate the change of permeability of concrete. Using this model, influence from moisture content on the measured permeability of existing concrete members can be considered as well.

The influence of moisture content on the permeability of concrete is shown in Figure 3. Jacobs (1994) measured the permeability of various concrete specimens with different moisture content. It can be observed that permeability decreases with increasing moisture content (water saturation). Based on the simplified approach by Bažant et al (1996), Darcy’s law is extended to the mix fluid of vapor and water. If the water saturation is zero, the flow is governed by vapor and the viscosity is that of vapor. If the water saturation is 100 %, then the flow is governed by the dynamic viscosity of water. With these boundary conditions, using the interpolation of viscosity, the permeability and viscosity can be given as:

$$k_{\mathrm{T}} = \begin{cases} k_0 \times 10^{C_{\mathrm{T}}(T_{\mathrm{M}}-T_0)}, & P_{\mathrm{VM}} < P_0 \\ k_0 \times 10^{C_{\mathrm{T}}(T_{\mathrm{M}}-T_0)} \left(\dfrac{P_{\mathrm{VM}}}{P_0}\right)^{C_P}, & P_{\mathrm{VM}} > P_0 \end{cases} \tag{5}$$

$$\mu = (1-w)\mu_V + w\mu_L \tag{6}$$

Where k_T is the permeability of concrete at temperature T, k_0 is the initial permeability of concrete at initial temperature T_0 under initial pressure P_0 (taken as ambient pressure 101 kPa), P_V the pore pressure, C_T and C_P are constants for the effects of temperature and pore pressure. w is the level of saturation, calculated by $(V_D+V_L)/(1\text{-}V_{S0}+V_D)$, V_L the volume fraction of liquid water, V_{S0} the initial volume fraction of solid and V_D the volume fraction of dehydrated liquid water. The temperature T_M and pore pressure P_{VM} are the maximum values in the entire heating process. As the permeability of concrete remains high after cooling from high temperature, the effect is determined by the heating history. In equation (1), the effect from pore pressure is considered only above the ambient pressure P_0, in the lower range the permeability will not be increased by the pore pressure. Dwaikat et al (2009) proposed that C_T be taken as 0.0025 and C_P as 0.368 based on the test results. In equation (6), μ_v is the dynamic viscosity of vapor and μ_L the dynamic viscosity of water. Using the form of Darcy's law, with μ as the dynamic viscosity of vapor, the permeability model can be rearranged as follows:

$$k_T = \begin{cases} \dfrac{k_0 \times 10^{C_T(T_M-T_0)}}{(1-w)+w\dfrac{\mu_L}{\mu_V}}, & P_{VM} < P_0 \\ \dfrac{k_0 \times 10^{C_T(T_M-T_0)}\left(P_{VM}/P_0\right)^{C_P}}{(1-w)+w\dfrac{\mu_L}{\mu_V}}, & P_{VM} > P_0 \end{cases} \tag{7}$$

In this way, the moisture content is considered in the change of permeability. The model is compared to the test results by Jacobs (1994). As shown in Figure 3, at ambient temperature, without the change of temperature and pore pressure, the predicted permeability change with the saturation agrees well with the test results.

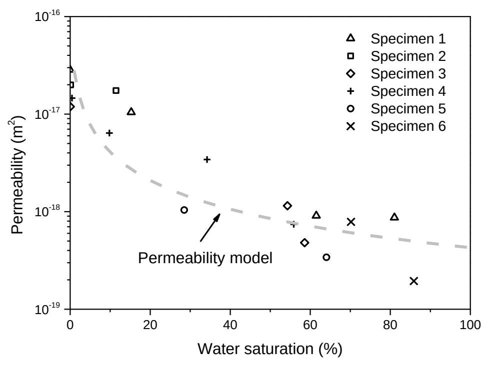

Figure 3. Comparison of predicted and measured permeability of concrete by Jacobs (1994).

At high temperature, the dynamic viscosity of vapor μ_v and the dynamic viscosity of water μ_L are given as following:

$$\mu_V = \mu_{V0} + a_V(T-T_0) \tag{8}$$

$$\mu_L = 0.6612 \times (T-T_0)^{a_L} \tag{9}$$

Where $\mu_{v0} = 8.85\times10^{-6}$ Pa S, $a_v = 3.53\times10^{-6}$ Pa S/K and $a_L = -1.562$.

For further validation of the permeability model at high temperatures, the proposed permeability model is implemented in the spalling model mentioned earlier. According to equation (7), the permeability changes with temperature, pore pressure and moisture content. The heating process is set the same as in the permeability measurement, using the same heating rate (Lu et al, (2016)). The predicted permeability from the model is compared with the measured permeability as shown in Figure 4, in which m_0 is the mass of liquid water. The wet specimen without pre-drying was simulated with 100 kg of m_0 in the model, the 3 days and 14 days pre-dried cases were assumed with 12 kg and 0.5 kg of liquid water. Figure 4 shows that the effects from moisture content, temperature and pore pressure are well-considered.

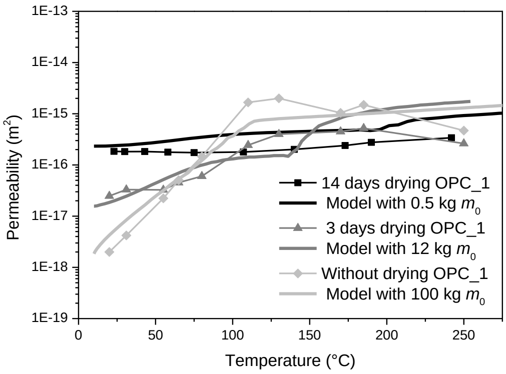

Figure 4. Comparison of predicted and measured permeability of OPC_1 (Lu et al (2016)).

In general, the permeability from the model agrees well with the test results, the various changes of permeability in different temperature ranges are predicted accurately. The permeability model is well-suited to predict the permeability of concrete.

For existing concrete members, the concrete permeability is measured with different moisture contents. As an option, core samples can be drilled and pre-dried in a furnace. Using the proposed permeability model, the concrete permeability can be measured by Torrent mothed directly on the surface. The influence from moisture content is considered by the permeability model. Together with the spalling model, this non-destructive test is well equiped to estimate the spalling risk of existing concrete members. This proposed method is validated against fire test result.

4 VALIDATION

The validation of the proposed method is established by comparing the prediction against test results. HPC members were heated according to the ISO fire curve (ISO-834) at the fire laboratory at EMPA (Swiss Federal Laboratories for Materials Science and Technology).

The investigated HPC mixture had a 28-day compressive strength of 103 MPa, and a slab with dimensions of $l \times w \times h$ = 1100 × 900 × 150 mm^3 was tested in a small horizontal furnace. The burners start with gas and then switch to oil due to its higher energy content. The temperatures at different depths of the concrete slab were measured by type K thermocouples. The fire spalling was observed after 14 minutes of fire exposure. If the test was not stopped manually after the initial spalling, the spalling would continue and depth would increase to 60 mm in 30 minutes (Klingsch et al (2013)). One of the tests was stopped manually when the initial spalling occurred with a loud cracking sound, as shown in Figure 5. The depth of the initial spalling was measured, the maximum depth reached 8 mm and the average depth was about 6 mm.

The permeability of the tested HPC slab was measured by Torrent permeability tester to be 1.05×10^{-18} m^2, while the initial moisture content was measured by means of a concrete moisture encounter (EMPA 2004) to be 3.1%. With these parameters, the predicted pore pressure and thermal stress were combined and spalling was predicted by the spalling model. As shown in Figure 6, the spalling stress $\sigma_{spalling}$ reached the reduced tensile strength of concrete at a depth of 7 mm after a total fire exposure time of t = 19 min. The predicted spalling depth of 7 mm agreed well with the test result, in which the initial spalling occurred at a similar position. The predicted spalling time was 5 minutes later than that in the test. Taking into consideration the uncertainty in high temperature properties, the prediction time of 19 minutes is acceptable. The spalling risk has been estimated by the proposed spalling model.

Figure 5. Initial spalling occurred in the test after 14 minutes.

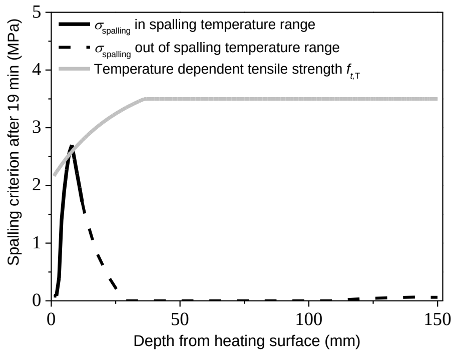

Figure 6. Spalling was predicted after 19 minutes.

In addition, the spalling model has been applied to estimate the effects from protective measures. Compared to test results, a good agreement was achieved in general (Lu et al (2017)). For existing members with high spalling risk, protective measures can be designed.

5 CASE STUDIES

Due to its advantages, the use of high performance concrete has become increasingly common in Switzerland, espesially for precast concrete elements, where high performance concrete has commonly been used since the early 1980s. These precast elements offer high strength and durability but are found more prone to fire spalling. In the Swiss design standard SIA 262, fire safety design is based on the assumption that no spalling occurs. To apply the tabulated design guideline, a low spalling risk is required.

To prove the validation of the designs in practice, we have cooperated with Urech Baertschi Maurer Consulting AG. The proposed spalling model has been used to evaluate the spalling risk in some existing building structures. As proposed, the permeability of the concrete is measured by the described non-destructive test. The compressive stresses in these members are taken from the global structural analysis of the building, usually from a finite element model. Using the spalling model, the spalling risk in these projects was determined considering the actual load. In cases with high spalling risk, protective measures were recommended according to the fire safety requirements.

Table 1 – Parameters of the cases.

	Project A	Project B
Fire safety requirement	R30 (30 minutes)	R90 (90 minutes)
Maximum concrete compressive Stress (MPa)	11	22
Minimum concrete permeability (m^2)	2.72e-17	1.02e-17
Saturation rate (-)	10%	10%

Many cases have been investigated in Switzerland. Project A and Project B are selected as examples to illustrate the use of the proposed method in practice. Permeability was measured in both cases without drilled cores, but on the column surface on site using a newly-designed test chamber. As shown in Figure 7 and Figure 8, the evaluated columns were not destructed. Only a small area of the paint coating on the surface was removed. The measured permeability is listed in Table 1. As dry ambient conditions were observed, moisture was not measured, but a conservative estimate was considered in the evaluation. The fire safety requirements are defined in terms of fire resistance classes R30 and R90.

Figure 7. Project A, permeability measurement on column.

Figure 8. Project B, permeability measurement on column,

With these parameters, the spalling risk was determined using the proposed spalling model. Due to low compressive stress and high permeability, no spalling was predicted in Project A. As shown in Figure 9, the spalling stress was not enough to induce explosive spalling during the first 60 minutes of ISO fire exposure. Therefore, in Project A, the design according to the tabulated data in the design standard provides enough fire resistance to achieve R30. As for Project B, explosive spalling was predicted after 41 minutes of ISO fire exposure. High compressive stress and low permeability lead to a significant rise of spalling stress during heating. The concrete surface can be expected to deteriorate and result in a fast increase in reinforcement temperature. The fire safety requirement R90 cannot be determined based on the tabulated data in design standard as the prerequisites of the application of the code table are not satisfied. Protective measures must be applied in Project B. As for the protective measure, 16 mm of a certain insulation plate was suggested in Project B, based on the prediction and previous test results (Lu et al (2017)).

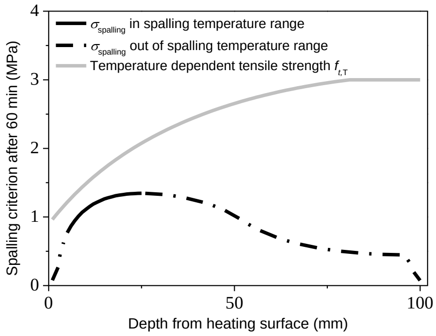

Figure 9. Spalling was not predicted within 60 minutes of ISO fire exposure in Project A.

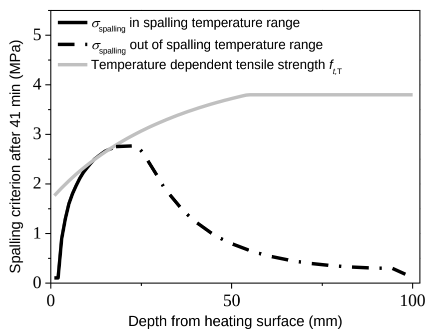

Figure 10. Spalling was predicted after 41 minutes of ISO fire exposure in Project B.

6 CONCLUSIONS

A method to assess the risk of concrete spalling in fire has been described. The key factors for concrete spalling have been considered. To estimate the spalling risk of existing concrete members, a permeability model has been proposed considering all three factors (temperature, pore pressure and moisture content). The model gives plausible results that lower permeability is predicted for specimens with high moisture content. The prediction from the method has been validated against fire test results, and a good agreement has been achieved. Therefore, the proposed method is considered as adequate for use with data from non-destructive tests. Some practical applications have been presented.

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