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Concrete Permeability and Explosive Spalling in Fire

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Abstract. Permeability of concrete is a good indicator of the risk of explosive spalling, concrete with low permeability is more prone to explosive spalling. To study explosive spalling of concrete, experimental tests on the concrete permeability have been carried out at ETH. The influences from temperature and moisture content have been investigated. The permeability of concrete is found to increase with the temperature and to decrease with moisture content. Based on the test results, a permeability model has been proposed. The explosive spalling has been predicted and an engineering boundary permeability for the liability to spalling is recommended to be 2×10^{-17} m^2 for a concrete slab heated according to ISO fire curve. The boundary permeability is influenced by moisture content, tensile strength and heating rate.

Introduction

Concrete is the most used building material in construction since many years due to its wide applicability and low cost. The fire resistance of concrete elements is usually good and the penetration of heat is slow, because concrete has a relatively high thermal capacity and low heat conductivity. With the development of modern technology and the increasing requirements for durability, concrete becomes denser, especially when silica fume is used to increase the concrete performance. High performance concretes (HPC) are more and more used in high-rise buildings or tunnels. Apart from the advantages of high density, high strength and good durability, the elements made of HPC have been reported more prone to fire spalling [1], leading to a reduced fire resistance. Therefore, explosive spalling of concrete induced by fire exposure has been a major concern in the use of HPC.

Since decades a lot of effort has been paid to study the nature of explosive spalling of concrete. Research has shown that the pore pressure is one of the most important parameters in explosive concrete spalling in fire [2] and the high pore pressure induced by the low permeability makes HPC more susceptible to explosive spalling. The permeability of concrete is a good indicator of the risk of explosive spalling. To predict the spalling of concrete, permeability measurements have been carried out at ETH Zurich. The test results indicate that the permeability of concrete is influenced by temperature, pore pressure and moisture content. A permeability model has been proposed to predict the permeability of concrete at high temperature. The risk of explosive spalling can be estimated considering the permeability.

Details of the permeability measurements and the permeability model will be presented in this paper. The boundary permeability of liability to spalling has been proposed using the permeability model.

Permeability measurements

The permeability of concrete varies with temperature and pore pressure. In addition, Jacobs [3] and Harmathy [4] indicated that the permeability is significantly influenced by moisture content. To interpret the influences from these factors, concrete specimens with different moisture contents have been investigated. Two methods, namely residual- and hot permeability have been compared and test results have shown that the two methods were in good agreement [13]. Therefore, the easily applicable residual permeability measurement will be chosen to investigate the effects from temperature, pore pressure and moisture content. The residual permeability is measured by the

Torrent method [5], as shown in Fig. 1. The concrete specimens were heated in the furnace and the residual permeability was measured after cooling.

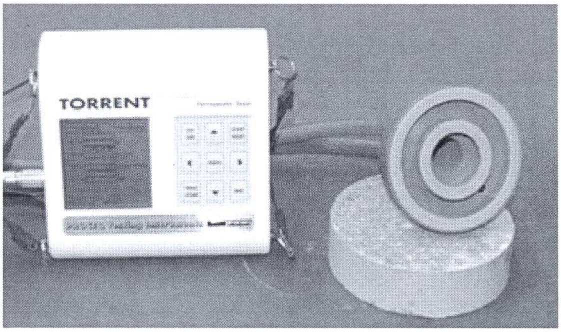

Fig. 1 Residual permeability measuring device according to the Torrent method.

Both specimens of ordinary Portland concrete (OPC) and high performance concrete (HPC) were studied, the properties of the mixes are listed in Table 1. After 28 days of moist curing, concrete cylinders with diameter 150 mm and height of 80 mm were dried at 105 °C for different durations. For the permeability measurement, to prevent much change in moisture content during the heat process, the specimens with different moisture contents were heated relatively fast, at the rate of 5 K/min to certain temperatures, and kept at the temperature for only 10 minutes.

Table 1 Mixtures of concrete to study the effect of moisture content.

Components	Units	HPC_1	OPC_1
Cement CEM I 52.5R	kg/m^3	580	-
Cement CEM I 42.5	kg/m^3		300
Silica fume	kg/m^3	63.8	-
Aggregate 0-8 mm	kg/m^3	1538	2010
Superplasticizer	kg/m^3	8.7	4.5
Water	kg/m^3	195.8	182.4
W/C ratio	-	0.34	0.61
28 day compressive strength	MPa	105	40

After various pre-dried periods the mass losses of the specimens were measured, the results are shown in Fig. 2. It can be seen that the drying process is faster at the beginning for both OPC and HPC mixtures. The mass of OPC is almost constant after 7 days of drying. The HPC's mass decreases more slowly, due to the low permeability. After pre-drying, the permeability measurements of the specimens with various initial moisture contents were carried out.

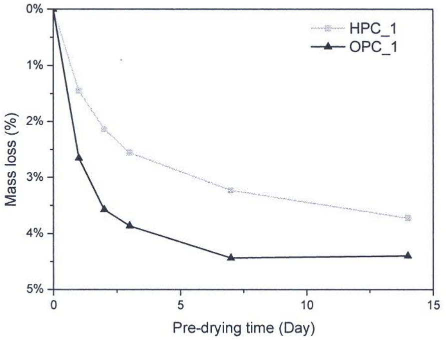

Fig. 2 Mass loss of concrete after pre-drying at 105°C.

The measured residual permeability of OPC is shown in Fig. 3, the test results of OPC specimens after 1 day, 3 days and 14 days of pre-drying are compared with the OPC without pre-drying. The permeability is plotted against the surface temperature after heating. Meanwhile, the mass losses of specimens after pre-drying have been measured (Fig. 4). The effect from moisture content is already noticeable at ambient temperature. Without pre-drying, the moisture content was high and the initial permeability was low. After 1 day of pre-drying, the moisture content decreased about 2.5% and the permeability increased about one order of magnitude. After 3 days of pre-drying, the loss of moisture content was around 4% and the permeability of OPC increased to over 1×10^{-16} m^2. For OPC, no significant difference was noticed when the specimens were pre-dried for longer time, which is attributed to the high permeability and fast drying process.

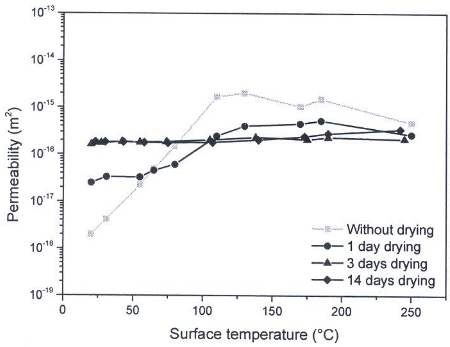

Fig. 3 Residual permeability of OPC with various moisture contents.

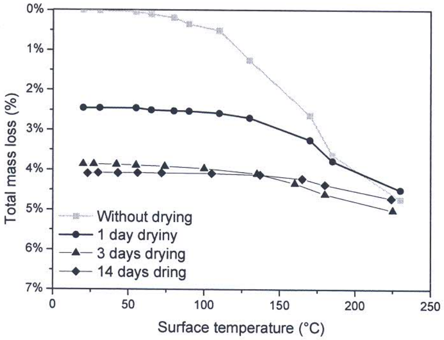

Fig. 4 Total mass loss of OPC after heating.

After heated to high temperatures, the effect from pre-drying is offset. The moisture content decreased more significantly in the specimens with high initial moisture content and the total mass losses were similar in all the specimens in the temperature range above 225 °C. The permeability of the specimens with high initial moisture content increased more significantly in the temperature range below 200 °C. At higher temperatures, no significant difference was noticed among the specimens. The fast increase of permeability is attributed to the decrease of moisture contents and high pore pressure in the wet specimens [2].

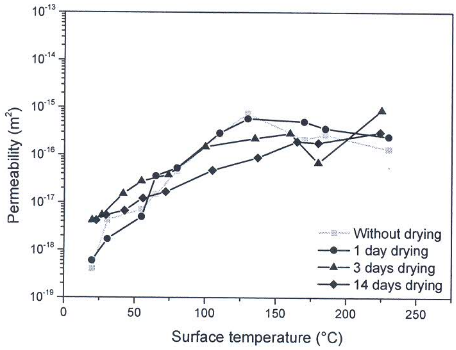

Fig. 5 Residual permeability of HPC with various moisture contents.

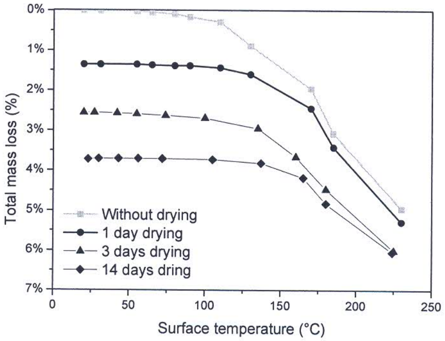

Fig. 6 Total mass loss of HPC after heating.

As for HPC, residual permeability and total mass loss are presented in Fig. 5 and Fig. 6. The drying process was slower and after 14 days of pre-drying, the permeability at ambient temperature changed less significantly than that in OPC. At high temperatures, higher initial moisture content induced higher permeability of HPC, which is similar in OPC. The pore pressure and moisture content are the main factors of the sharp increase in wet specimens.

It can be seen that at ambient temperature the permeability of concrete changes with moisture content, high moisture content results in low permeability. Similar results have been reported by Jacobs [3] (see Fig. 7). Apart from moisture content, the permeability of concrete increases generally with temperature and pore pressure.

Permeability model

The permeability measurement has shown that the permeability of concrete is a function of temperature, pore pressure and moisture content. Based on the test results, a permeability model has been proposed to calculate the change of permeability of concrete.

The influence of moisture content on the permeability of concrete is shown in Fig. 7. Jacobs measured the permeability of various concrete specimens with different moisture content. It can be seen that the permeability decreases with the moisture content (water saturation). Based on the simplified approach by Bazant and Kaplan [6], Darcy's law is extended to the mix fluid of vapor and water. If the water saturation is zero, the flow is governed by the vapor, then the viscosity is the viscosity of vapor; if the water saturation is 100 %, then the flow is governed the dynamic viscosity of water. Taken as the boundary condition, using the interpolation of viscosity, the permeability and viscosity can be given as:

$$k_{\mathrm{T}} = \begin{cases} k_0 \times 10^{C_{\mathrm{T}}(T_{\mathrm{M}}-T_0)}, & P_{\mathrm{VM}} < P_0 \\ k_0 \times 10^{C_{\mathrm{T}}(T_{\mathrm{M}}-T_0)} \left(\dfrac{P_{\mathrm{VM}}}{P_0} \right)^{C_P}, & P_{\mathrm{VM}} > P_0 \end{cases} \tag{1}$$

$$\mu = (1-w)\mu_{\mathrm{V}} + w\mu_{\mathrm{L}} \tag{2}$$

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 $(V_{\mathrm{D}}+V_{\mathrm{L}})/(1-V_{\mathrm{S0}}+V_{\mathrm{D}})$, 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. Because 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 and Kodur [7] proposed that C_{T} be taken as 0.0025 and C_{P} as 0.368 based on the test results. In Equation 2, μ_{v} is the dynamic viscosity of vapor and μ_{L} the dynamic viscosity of water. Using the form of Darcy's law, with the μ as the dynamic viscosity of vapor, the permeability model can be rearranged as following:

$$k_{\mathrm{T}} = \begin{cases} \dfrac{k_0 \times 10^{C_{\mathrm{T}}(T_{\mathrm{M}}-T_0)}}{(1-w)+w\dfrac{\mu_{\mathrm{L}}}{\mu_{\mathrm{V}}}}, & P_{\mathrm{VM}} < P_0 \\ \dfrac{k_0 \times 10^{C_{\mathrm{T}}(T_{\mathrm{M}}-T_0)} \left(P_{\mathrm{VM}}/P_0 \right)^{C_P}}{(1-w)+w\dfrac{\mu_{\mathrm{L}}}{\mu_{\mathrm{V}}}}, & P_{\mathrm{VM}} > P_0 \end{cases} \tag{3}$$

In this way, the moisture content is considered in the change of permeability. The model is compared to the test results by Jacobs (1994). Shown in Fig. 7, at ambient temperature, without the change of temperature and pore pressure, the predicted permeability change with the saturation agrees well with the test results.

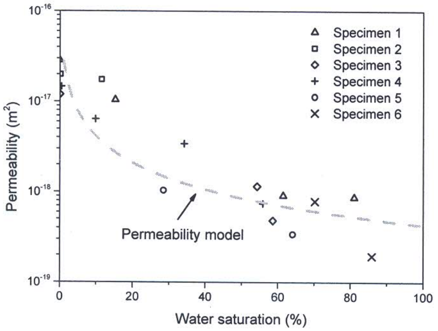

Fig. 7 Comparison of predicted and measured permeability of concrete by Jacobs [3].

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

$$\mu_V = \mu_{V0} + a_V (T - T_0) \tag{4}$$

$$\mu_L = 0.6612 \times (T - T_0)^{a_L} \tag{5}$$

Where $\mu_{V0} = 8.85\times10^{-6}$ Pa S, $a_V = 3.53\times10^{-6}$ Pa S/K and $a_L = -1.562$.

To further validate the permeability model at high temperature, the proposed permeability model is applied in the thermos-hydro model [2]. According to Equation 3, the permeability changes with the temperature, pore pressure and moisture content. The heating process is set the same as in the permeability measurement, using the same heating rate. The predicted permeability from the model is compared with the measured permeability as shown in Fig. 8, in which the m_0 is 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. It can be seen that the effects from moisture content, temperature and pore pressure are well taken into account.

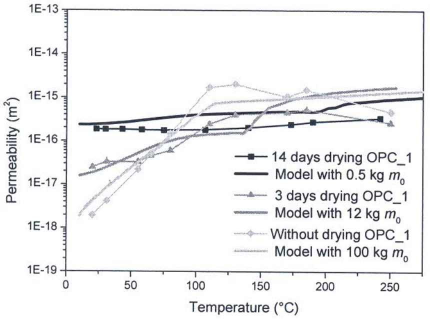

Fig. 8 Comparison of predicted and measured permeability of OPC_1.

The significant change of initial permeability with the moisture content was well predicted. With 100 kg of liquid water (m_0), the permeability of OPC_1 without pre-drying was about two orders of magnitudes lower than that of 14 days pre-dried OPC_1 with 0.5 kg of liquid water (m_0), which agreed well with the test results. At high temperatures, the predicted permeability increased generally in accordance with the measured values. Considering the influence from pore pressure in the