



Permeability measurement on high strength concrete without and with polypropylene fibers at elevated temperatures using a new test setup



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ABSTRACT

A new test setup for permeability measurement at room and high temperature is presented. The experimental results obtained by employing the new setup are reported and validated. The experiments are performed on high performance concrete, without and with addition of polypropylene fibers under temperatures ranging from 20 °C to 300 °C as well as after cooling of previously heated specimens to the room temperature. The results show that plain concrete exhibits steady increase in permeability with increasing temperature, whereas concrete with fibers exhibit a sudden increase of permeability at temperatures between 80 °C and 130 °C. The results confirm the governing role of permeability on explosive spalling and suggest the existence of mechanisms of pressure relief other than just melting of fibers. The microstructure of concrete with fibers is investigated using SEM before and after exposure to high temperature. It is observed that the melted polypropylene flows only into the micro-cracks and does not penetrate into cement paste.

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1. Introduction

Available pore space and the connectivity of pores govern the ingress and transport of gases and liquids into porous materials and, consequently, the durability of these materials. The pore volume is characterized by porosity and the connectivity of pores by permeability. These two properties together govern the durability of porous materials such as concrete. High strength and high performance concretes have a very dense cement paste structure, which results in low porosity and permeability. In general, lower permeability results in higher durability since the aggressive media cannot ingress in concrete easily. This is valid for the case of ingress of liquids and gases which can adversely affect the concrete or reinforcement behavior.

However, at elevated temperatures, e.g. in case of fire, less permeable concretes become susceptible to the phenomenon of explosive spalling of concrete cover. When the surface of concrete element is heated, water vapor tends to migrate towards the surface as well as towards the core of the concrete element. If the concrete is not sufficiently permeable to allow the vapor to move, a fully saturated front is formed. This front prevents vapor movement into the concrete and causes generation of high pore pressures, which in combination with thermal stresses can trigger explosive spalling. Explosive spalling is a very violent form of concrete failure characterized by bursting and forcible separation of pieces of concrete, accompanied by a typically loud explosive noise. Low permeability of high performance concrete (HPC) typically makes it more susceptible to this dangerous failure mode. Namely,

because of spalling of concrete cover reinforcement can directly be exposed to high temperature, which can dramatically reduce safety of reinforced concrete structure. Probably the most efficient method for reducing the risk of explosive spalling is the addition of polypropylene (PP) fibers.

Various experimental and numerical studies have demonstrated the influence of permeability on explosive spalling [1–3]. Experimental studies of permeability were performed by employing different permeating media (gases and liquids) as well as different measurement methods, since currently there is no generally accepted testing method. Some of the laboratory measurement methods that use liquids (water) as medium are: constant head experiment [4] and falling head experiment [5]. The methods using gases (oxygen, nitrogen, helium) as medium are: the RILEM-CEMBUREAU method [6] and the Hassler method [2]. In general, permeability to an inert gas yields more realistic values than permeability to water, since water addition in concrete can result in rehydration of un-hydrated cement.

The vast majority of the experimental studies on the influence of temperature on permeability were performed in residual state, i.e. after cooling the specimens to room temperature [2,7,8]. Only very limited studies aimed at measuring permeability on heated specimens can be found in the literature [3,9–11]. This is mainly due to the technical difficulties involving measurements of permeability at elevated temperatures. Nevertheless, it is important to measure the material properties directly at elevated temperatures to understand the phenomenon occurring at high temperature. It is also interesting to compare them with their residual counterparts.

Another very important aspect from the viewpoint of explosive spalling is the influence of addition of PP fibers. According to

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experimental evidence, explosive spalling occurs typically at temperatures between 200 °C and 250 °C, while PP fibers melt at approx. 160 °C to 170 °C. Therefore, it is reasonable to assume that the melted fiber leaves free path for the water vapor to escape. Thus, the pore pressure is relieved and hence no or very limited spalling occurs. However, it is still not very clear what happens with the fibers after melting. Kalifa [2] suggests that the melted polypropylene is absorbed by the cement matrix and thus empty fiber beds are available for pressure relief. Khoury [12], on the other hand, considers diffusion of polypropylene into cement matrix impossible because of the large molecule size, i.e. high viscosity of the fiber melt. He suggests that prior to melting of fibers, the contact between the fibers and matrix becomes permeable to water vapor. This topic requires further experimental investigation of the concrete microstructure.

Here, a new test setup for permeability measurement of concrete at high temperature is presented. The setup is relatively simple and easy to operate while being reasonably accurate at the same time. It is validated against the widely used RILEM-CEMBUREAU method [6] for permeability measurements at room temperature. Using the new test setup, experiments are performed on concrete without and with added PP fibers subjected to thermal loads in range between 20 °C and 300 °C. Permeability to nitrogen is calculated by employing the pressure decay method. In order to provide more insight into the concrete microstructure after exposure to elevated temperature, microscopic investigations are performed on concrete containing fibers before and after exposure to elevated temperature. In the following sections the theoretical background, test methodology, material properties and results are presented and discussed.

2. Theoretical background

One-dimensional laminar flow in a porous material is described by Darcy's law:

$$Q = -k \frac{A dp}{\eta dx} \quad (1)$$

where: Q [m³/s] is the volumetric flow, k [m²] is the permeability, A [m²] is the area of the specimen perpendicular to the flow direction, dp/dx [Pa/m] is the pressure gradient and η [Pa·s] is the viscosity of the permeating fluid. Intrinsic permeability describes the ability of a porous material to resist fluid ingress. It depends only on the geometry and connectivity of the porous network, and not on the pressure of the permeating fluid. For incompressible fluids the permeability k as given in Eq. (1) corresponds to the intrinsic permeability. However, the same is not true for compressible fluids, since the permeability obtained from Eq. (1) is dependent on pressure. Therefore it is denoted as apparent permeability and it is valid for the specific pressure at which the permeability is measured.

When gases are transported through porous media, the flow consists of viscous flow as well as slip flow. The slip flow phenomenon is present in the case when the pore size is of the same order of magnitude as the mean path of the gas molecules, in which case the molecules slide on the pore walls. The mean free path describes the average distance covered by a moving particle (atom, molecule) between successive impacts and is inversely proportional to pressure [13]. Klinkenberg [13] suggested a method to correct the apparent permeability in order to obtain intrinsic permeability. The formulation reads:

$$k = k_{\text{int}} \left(1 + \frac{b}{p_m} \right) \quad (2)$$

where: k [m²] is the apparent permeability, k_{int} [m²] is the intrinsic permeability, b [Pa] is the Klinkenberg "slip flow constant" and p_m [Pa] is mean of the pressures between the inner and outer face of the specimen, thus one of them always being atmospheric pressure,

i.e. $p_m = (p_1 + p_2)/2$, where p_1 corresponds to the inlet pressure and p_2 to the outlet pressure (atmospheric pressure). The slip flow constant b is a function of gas and porous system. It is inversely proportional to the average diameter of the capillaries.

The following is valid for compressible fluids:

$$Qp = \text{const} = Q_m p_m \quad (3)$$

where p_m is the mean pressure and Q_m is the volumetric flux corresponding to the mean pressure.

The specimens used in the experiments are hollow cylinders with inner radius r_1 , outer radius r_2 and height H (see Fig. 1). Multiplying Eq. (1) with p and integrating from r_1 to r_2 , following can be obtained:

$$Q_1 p_1 \int_{r_1}^{r_2} dr = -k_{\text{int}} \frac{A p_2}{\eta p_1} \int (b + p) dp. \quad (4)$$

After integration and solving the equation for k :

$$k = \frac{\eta \ln\left(\frac{r_2}{r_1}\right)}{\pi H} \frac{Q_1 p_1}{(p_1^2 - p_2^2)}. \quad (5)$$

Under the assumption of ideal gas, Clapeyron's law can be applied:

$$nRT = p_1 V \quad (6)$$

where: n [mol] is the amount of substance, R [J/mol K] is the ideal gas constant, T [K] is the temperature and V [m³] is the volume occupied by gas. Thereby, isothermal conditions are assumed, i.e. temperature is constant during measurement at each of the target temperatures. Since the volume of the pressurized gas is also constant, following is valid:

$$\frac{dn}{dt} RT = \frac{dV p_1}{dt} = Q_1 p_1 = \text{constant}. \quad (7)$$

For a certain time interval Δt , Clapeyron's law can be rewritten as:

$$\frac{\Delta n}{\Delta t} = \frac{\Delta p_1 V}{RT} \Rightarrow \frac{\Delta n}{\Delta t} \approx Q_1 p_1 \frac{1}{RT} \quad (8)$$

and

$$Q_1 p_1 = \frac{\Delta p_1 V}{\Delta t}. \quad (9)$$

Using Eq. (9) in Eq. (5) the following relation is obtained:

$$k = \frac{\eta \ln\left(\frac{r_2}{r_1}\right)}{\pi H} \frac{\frac{\Delta p_1 V}{\Delta t}}{(p_1^2 - p_2^2)}. \quad (10)$$

In each time interval Δt , the apparent permeability k is calculated according to Eq. (10). Pressure decay history is obtained from the experiment. The dynamic viscosity of gases is a function of temperature. This is accounted for when calculating the permeability. In order to obtain the intrinsic permeability, the apparent gas permeability is extrapolated to the infinite mean pressure ($1/p_m = 0$), as shown in Fig. 2.

3. Experimental investigations

3.1. Test setup

In the experimental investigations two different test setups are used. Namely, in order to verify the new experimental setup for measurement of permeability of concrete at high temperature, the experiments

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