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The Effect of Loading on the Residual Gas Permeability of Concrete

Md Jihad Miah^{1,2}, Hatem Kallel¹, H  l  ne Carr  ¹, Pierre Pimienta²,
Nicolas Pinoteau², Christian La Borderie¹,
Francesco Lo Monte³ & Roberto Felicetti³

¹ISA BTP-SIAME, Universit   de Pau et des Pays de
l'Adour, F  d  ration IPRA, EA4581, 64 600, Anglet, France.

²Centre Scientifique et Technique du B  timent (CSTB),
Universit   Paris Est, F-77447 Marne La Vall  e, France

³Department of Civil and Environmental Engineering,
Politecnico di Milano, Milan, Italy

ABSTRACT

Permeability is related to the interconnectivity of the pores in the concrete, which measures how fast the gases or liquids will flow through it due to a pressure gradient. Knowledge of permeability will allow us to better understand the fluid transport behaviour in concrete, which could influence its fire spalling behaviour by directly influencing the build-up of pore pressure during heating. Three different gas permeability tests were carried out in SIAME and CSTB on 2 concretes B40-II (3% of slag) and B40-III (43% of slag). They are as follows: i) Residual axial permeability tests under radial confining pressure after unloaded preheating, ii) Residual axial permeability tests under radial confining pressure after preheating under uniaxial loading and iii) Residual radial permeability tests under uniaxial loading. The experimental test results have clearly shown that the presence of loading and their levels have a significant influence on the permeability of concrete. The permeability increase or decrease depends on the orientation and opening of cracking and these two parameters are influenced by compressive loading. The permeability of B40-III (much higher amount of slags) is more sensitive than B40-II in all heating and loading conditions.

KEYWORD: concrete, temperature, permeability, confining pressure, compressive loading, cracking, slag.

INTRODUCTION

Fire spalling of concrete is a complex phenomenon, which might occur due to pressure build-up in the pores and thermal and load-induced stresses [1]. In one of our recent study, it has been shown that the loaded specimens are more susceptible to fire spalling than unloaded specimens, with increasing amount of spalling for higher values of applied load (uniaxial and biaxial load) [2]. It was also found that the fire spalling behaviour of concrete slabs in unloaded condition (0 MPa) and under a very small biaxial load (0.5 MPa, parallel to the heated face of the slab) can present two different scenarios. In the first case, no spalling has been observed in the unloaded specimen. In the second one, a uniform erosion extended to the whole heated area has been observed, for an average spalling depth of 12 mm. This higher spalling behaviour could be explained not only because of the higher stresses (induced by the higher external load) but also by the higher pore pressure induced by a lower damage state and permeability [3-5]. Felicetti and Lo Monte 2016 [5], by implementing on the same biaxial fire tests an innovative technique based on ultrasonic pulse-echo have shown that damage was significantly reduced when slabs were loaded, even at a very low biaxial stress (0.5 MPa). Limited biaxial loads then can apparently affect in a non-negligible way the thermally

induced microcracking and then reduce concrete permeability at high temperature.

In the literature, a number of studies have been conducted on the permeability of concrete at high temperatures on the unloaded condition [6-9], while comparatively, there are few published data on the permeability of concrete subjected to heating and mechanical loading or under confining condition [4, 10-12]. Pei et al. 2017 [10] carried out permeability and porosity tests under different levels of confining pressure (5, 10, 20, 30 and 40 MPa). In their study, mortar specimens (37 mm in diameter and 70 mm long cylinder) were heated to 105, 400, 500 and 600°C with a heating rate of 20°C/h. Their results showed that permeability has an increased sensitivity to confining pressure at higher temperatures due to the closure of the cracks. Chen et al. 2013 [11] tested the gas permeability of heat-treated mortars at four different levels of confining stresses ($P_c = 5, 12, 15$ and 25 MPa). The authors observed that the permeability of mortars heat-treated above 400°C was sensitive to confining pressure and the intrinsic permeability decreased by up to 23% when the confining stress increased from 5 to 25 MPa. Lun et al. 2013 [12] tested the gas permeability of concrete under thermal (up to 350°C) and uniaxial compressive stress (5, 10, 15 and 20 MPa). A reduction of the permeability was observed at compressive stress levels at 5 and 10 MPa, while an increased permeability was observed for the specimens loaded at 15 and 20 MPa. Choinska et al. 2007 [4] showed that the permeability of concrete during heating under uniaxial compressive loading (stress levels lower than 80% of the peak stress) is smaller than the permeability measured after unloading.

In order to summarise, during a real fire, concrete structural members are always loaded or restrained. The presence of an external load during heating may play an important role in the development of cracking (i.e. permeability), which can influence the magnitude of the pore pressure and then the risk of fire spalling.

In order to gain a deeper understanding of the role of loading on the permeability of concrete, the presented research aims to complete the existing results. Three different tests have been conducted. This extensive experimental campaign was conducted on the same 2 concretes mixes (B40-II and B40-III), we have carried out fire spalling tests under uniaxial and biaxial load [2].

EXPERIMENTAL INVESTIGATION

Materials and mix design

Two ordinary concretes (B40-II and B40-III) made respectively, with CEM II (CEM II/A-LL 42.5 R CE CP2 NF) and CEM III (CEM III/A 42.5 N CE CP1 NF) cements have been investigated. The same mix design was used for both concretes; the only difference is the cement type. The CEM II cement contains 85% of clinker, 12% of limestone and 3% of slag, while the CEM III cement contains 54% of clinker and 43% of slag, and 3% of limestone. The compressive strengths (f_c) of B40-II and B40-III concretes determined on cylinders (\varnothing 160 mm x h 320 mm) are, respectively, 41.7 MPa and 41.0 MPa at 28 days and 51.2 MPa and 50.4 MPa at 90 days. Further details about mix design and mechanical properties of these concretes are presented in Miah et al. 2015 [9].

Test program

In order to gain a deeper understanding of the role of different loading conditions in compression on the permeability of concrete, 3 different gas permeability tests were carried out in SIAME and CSTB. They are as follows:

- i) Residual axial permeability tests under radial confining pressure after unloaded preheating,
- ii) Residual axial permeability tests under radial confining pressure after preheating under uniaxial loading,
- iii) Residual radial permeability tests under uniaxial loading.

The experimental program is described in Table 1. Testing temperatures, applied compressive stresses and number of tested samples are given. Except test iii) at 600°C, two specimens for each temperature and each compressive load were used for both concretes, see Table 1.

Table 1 Experimental program (Note: – = No test, B40-II/B40-III).

T [°C]	80	120	250	400	600	800
i) Residual axial permeability tests under radial confining pressure ($\sigma = 0$ and $P_c = 0.3, 0.6, 0.9$ and 1.2 MPa)	2/2	2/2	2/2	2/2	2/2	2/2
ii) Residual axial permeability tests after heating-cooling under uniaxial loading ($\sigma = 0, 0.5, 1.5, 3$ and 5 MPa and $P_c = 0.6$ MPa)	–	–	–	2/2	–	–
iii) Residual radial permeability tests under uniaxial loading ($\sigma = 0.6, 0.9, 1.2, 2, 3, 5$ and 10 MPa)	–	2/2	2/1	2/2	1/–	–

The detail descriptions of the test methods are described in the sections below.

Apparatus and test procedures

i) Residual axial permeability tests under radial confining pressure after unloaded heating

The residual axial gas permeability of concrete was measured on 150 mm diameter and 50 mm thickness concrete disc using a Cembureau constant pressure permeameter, see Figure 1 [13]. The permeability of concrete was investigated at room temperature after applying thermal loads of 120, 250, 400, 600 and 800°C at a slow heating rate of 1°C/min. The slow heating rate of 1°C/min was chosen to limit undesirable thermal stress. After reaching the target temperatures, the temperatures were stabilised for 28, 10, 6, 6 and 6 hours, respectively, for the temperatures of 120, 250, 400, 600 and 800°C [14] to reach a uniform temperature in the concrete. The reference specimens were dried in an oven at 80°C until a constant value of mass was reached. The specimens were then cooled down to room temperature at a rate of 0.3°C/min inside the closed furnace. To study the effect of confining pressure (perpendicular to the gas flow) on the gas permeability of concretes (B40-II and 40-III), four different levels of radial confining pressure, P_c ($P_c = 0.3, 0.6, 0.9$ and 1.2 MPa, see Table 1) has been investigated. This was achieved by increasing the inflatable rubber tube pressure applied to the polyurethane rubber ring, see Figure 1 left. To ensure that the lowest applied load (0.3 MPa) is sufficient to prevent leakage of gas through the curved side, blank tests on an aluminium disc of the same dimensions (150 mm diameter and 50 mm thickness) were performed at 0.3 and 0.6 MPa. No outflow occurred at these lower confining pressures. Therefore, these blank tests demonstrated that the permeability test results on the concrete specimens were not affected by leakage through the curved side even when applying the lower load value.

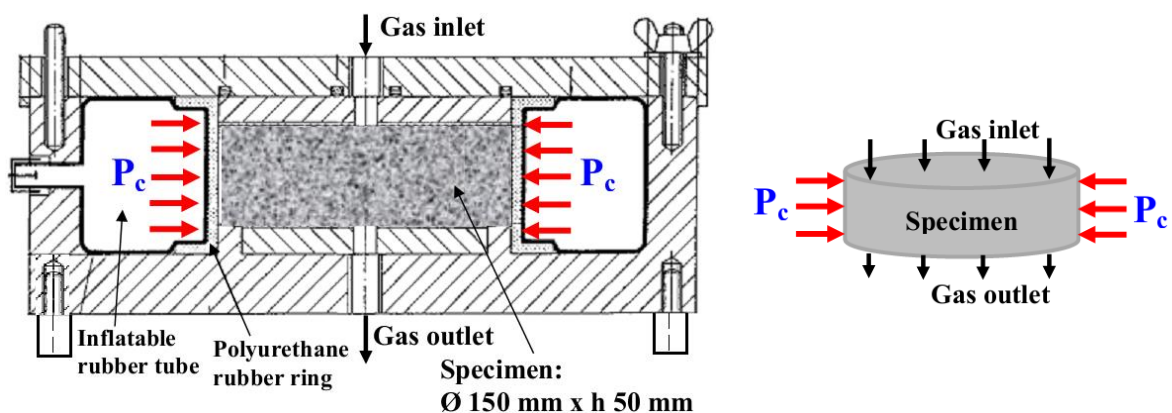


Figure 1 Test setup according to the RILEM-CEMBUREAU method (left) [13] and detail application of confining pressure (P_c) and axial gas flow to the specimen (right).

Nitrogen has been chosen as the neutral percolating gas. Three levels of pressure difference ΔP (the difference between the injection pressure P_i and the atmospheric pressure P_{atm}) were chosen depending on preheating temperatures in order to determine the intrinsic permeability of concretes according to the Klinkenberg's approach [15]. Inlet pressures were applied and maintained until gas flow stabilisation.

ii) Residual axial permeability tests under radial confining pressure after preheating under uniaxial loading

Method ii) was very similar to method i). The main difference was that the specimens were preheated to ambient temperature under a constant uniaxial compressive loading, see Figure 2. The size of the specimens was the same. In order to be heated under the testing machine, samples were surrounded with a heating foil (see the second image in Figure 2) and a thermal insulator made with ceramic wool. Only one heating temperature (400°C) was studied and the permeability tests were performed with one confining pressure (0.6 MPa).

Prior heating, all the specimens, as well as concrete supports, were grinded in order to obtain two faces (upper and lower face) parallel and plane to uniform the stress distribution in the specimens. They were then heated at 1°C/min up to 400°C, stabilised for 8 hours, and then cooled down to ambient temperature inside the heating device. Before heating, a constant uniaxial compressive load was applied and then maintained constant during heating and cooling. Five different levels of uniaxial compressive stresses have been investigated on both concretes (B40-II and B40-III), see Table 1.

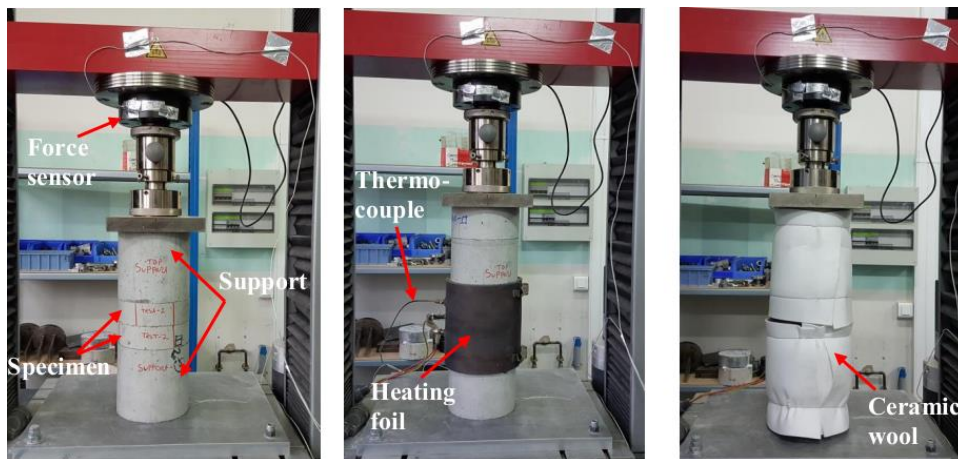


Figure 2 Method ii) – Preheating under uniaxial loading.

iii) Residual radial permeability tests under uniaxial loading

The principle of this test was to measure the radial permeability by injecting the nitrogen gas inside a hollow concrete cylindrical disc and then measure the radial gas flow of the specimen. The size of the hollow discs was 123 mm in outer diameter and 52 mm internal diameter with 50 mm in height, see Figure 3. The top and bottom faces of the specimens were ground and sealed with aluminium foil tape to prevent leakage of gas along the interface. The heating rate and the temperature levels were same as described in Section i).

A schematic diagram of the experimental device is shown in Figure 4. This experimental setup allows the measurements of radial gas permeability. First, the specimen was placed in the cell of permeameter composed of a system with two metal platens. Then, the inert gas (nitrogen) was injected into the cylindrical borehole through the perforated bottom platen. A pressure difference ΔP (the difference between the injection pressure P_i and the atmospheric pressure P_{atm}) was applied and maintained until gas flow stabilisation. The relative pressure and mass flow rate were measured at the upstream of the specimen by the flowmeters, after that the volumetric gas flow was calculated.

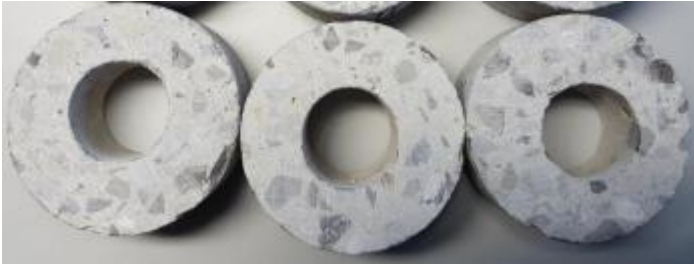


Figure 3 Radial permeability test specimens.

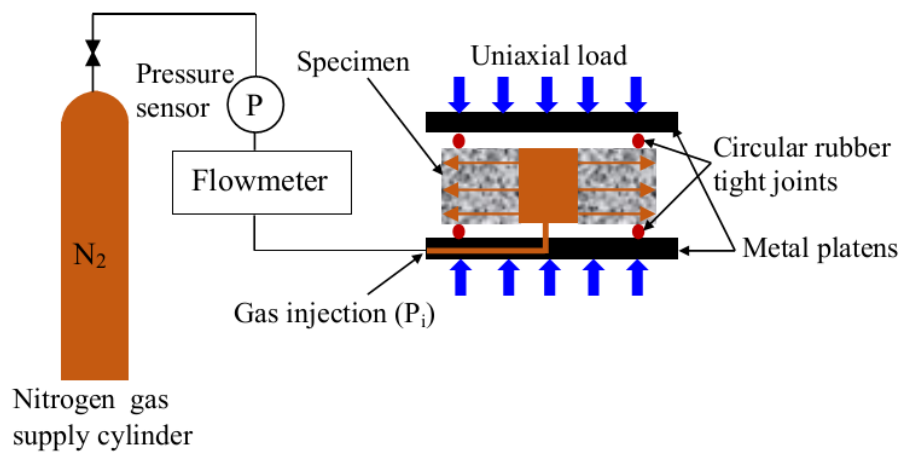


Figure 4 Schematic diagram of the residual radial permeability test under uniaxial loading device.

A small constant uniaxial compressive stress of 0.6 MPa was applied. This small load ensures the tightness of the permeability cell, hence, radial gas flow only. This permeability assumed as reference permeability for this test program, since it is believed that this small load will not modify significantly the crack pattern of the specimen. To study the effect of uniaxial compressive loading on the radial gas permeability of concrete, seven different levels of compressive loading have been investigated on both concretes (B40-II and B40-III), see Table 1. Four different levels pressure difference ΔP were applied to the samples depending on preheating temperatures in order to determine the intrinsic permeability of concretes according to the Klinkenberg's approach [15].

EXPERIMENTAL RESULTS

i) Residual axial permeability tests under radial confining pressure after unloaded preheating

Figure 5 presents the effect of confining pressure on the residual axial intrinsic permeability (K_{int}) of concretes (B40-II and B40-III) specimens subjected to different preheating temperatures. It can be seen that as the temperature increased, the permeability increased with higher increment at the higher thermal load, see Figure 5a. In the graph, the lines represent the average value and the vertical line (i.e. error bar) represents the range of data. The results were reproducible. At temperatures ranging from 80°C to 120°C, a bit sharp increase of permeability was observed for both concretes. This behaviour could be due to accessible pore volume caused by the withdrawal of free and physically bound water that could not be withdrawn at 80°C (as reported in [16]). This sudden upward jump of permeability was also observed by Bazant 1997 [17], which was more than 2 orders of magnitude (about 200 times) when passing from 95°C to 105°C. It can be seen that as the temperature increased, the permeability increased, especially higher increment at the higher

thermal load. At a temperature higher than 400°C, the increased permeability is attributed to the development of cracks mainly caused by the thermal incompatibility between the cement paste and the aggregates, since at high temperature the cement paste shrinks due to dehydration, while the aggregates dilate due to their positive thermal expansion [16].

The experimental results showed that the axial permeability of the 2 concretes (B40-II and B40-III) decreased with increasing radial confining pressure (P_c perpendicular to the gas flow, see Figure 1 right). It can be seen that the residual permeability after preheating at 80°C and 120°C are quite insensitive to confining pressure. This could be due to the reduced amount of microcracks and cracks induced by the lower thermal loads. By opposite, these effects are more pronounced as the temperature treatment has been increased (e.g. at 600°C and 800°C). It is important to notice that, as written before, the decreased trend of permeability is not due to leakage of gas, since no outflow occurred at confining pressure starting from 0.3 MPa during the blank test. This behaviour could be attributed to the partial closure of heat induced microcracks and cracks (perpendicular to the gas flow) probably located at the aggregate-cement paste interface as well as through the aggregates when the specimens were compressed by the radial confining pressure. Indeed, the width of cracks perpendicular to the applied compressive stress (here stress due to confining pressure) closed [10] while those parallel to the stress tended to open [18-20].

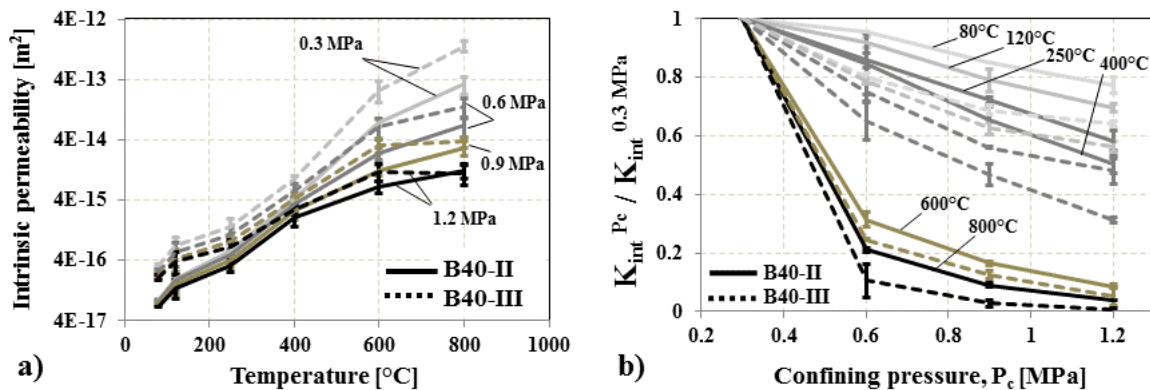


Figure 5 Residual axial intrinsic permeability (K_{int}) of concretes under different levels of confining pressure (P_c) as a function of temperature (a) and normalised permeability versus P_c (b).

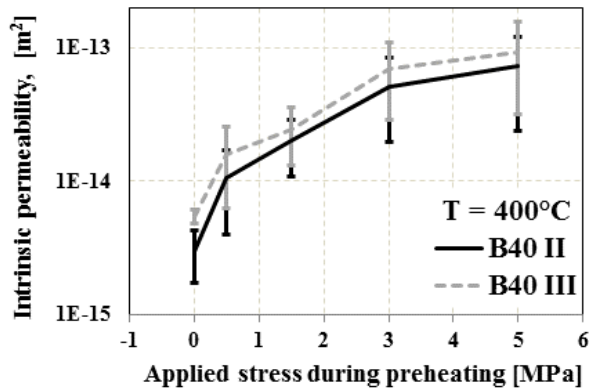
Interestingly, a sharp decrease of permeability can be seen when the confining pressure was doubled ($P_c = 0.6$ MPa) than the reference pressure ($P_c = 0.3$ MPa). When the confining pressure continues to increase beyond 0.6 MPa, the rate of decreasing trend seems to be much smaller, and the permeability tends to stabilise for the high thermal loads, while it continues to decrease for the intermediate thermal loads (e.g. at 250°C and 400°C). From the Figure 5b, it can suggest that the cracks closure and the decrease in permeability could continue if the confinement would have been increased beyond 1.2 MPa (which was the limitation of the test device), in particular for the specimens which were exposed to intermediate temperatures. The presented results are in good agreement with the results reported in the literature even though most of the studies have been carried out at confining pressures that are much higher than in our tests [10-11].

Figure 5 allows us to compare the axial gas permeability of B40-II (3% of slag) and B40-III (43% of slag). We can observe that permeability of B40-III is higher for all the temperatures under 0.3 MPa confining pressure. This difference decreases when confining pressure increases.

ii) Residual axial permeability tests under radial confining pressure after preheating under uniaxial loading

Interestingly, an increasing trend of intrinsic axial gas permeability was observed with the increased uniaxial compressive loading (parallel to the gas flow) during heating-cooling, see Figure 6a. When concrete is heated under a constant uniaxial compressive load, its longitudinal strain is reduced. This

reduction is mostly induced by transient thermal strain [18]. By opposite, radial strains tend to be higher. This is mainly explained by the formation and opening of cracks parallel to the loading [18-20]. The evidence of cracks parallel to the loading direction after heat treatment at 400°C under uniaxial loading (5 MPa) can be clearly seen in Figure 6d. No similar cracking was observed in the unloaded specimens, see Figure 6c. These axial cracks explain the higher axial gas permeability measured in these tests, since the injected gas flow was axial to the loading direction of the specimens.



a) Axial permeability versus applied stress during preheating

b) Image of B40-III preheated under a compressive stress $\sigma = 5$ MPa



c) Image of B40-III preheated under a compressive stress $\sigma = 0$ MPa



d) Image of B40-III preheated under a compressive stress $\sigma = 5$ MPa

Figure 6 Effect of uniaxial compressive loading (parallel to the gas flow) during preheating on the axial permeability of the 2 concretes (B40-II and B40-III).

B40-II (3% of slag) exhibited lower permeability than the B40-III (43% of slag), which is in good agreement with the former tests we have presented in Section i.

iii) The effect of uniaxial loading on the residual radial permeability

Figure 7a presents the residual radial intrinsic permeability (K_{int}) of concretes (B40-II and B40-III) as a function of uniaxial compressive stress, while the relationships between the normalised permeability and the uniaxial compressive stress are shown in Figure 7b. It can be seen that in Figure 7a-b, at lower temperatures (120 and 250°C), permeability decreases when applied compressive stress increases, while at the higher temperatures (400°C and 600°C), the permeability decreases up to a certain level of load, after that stabilises and then increases when the compressive stress increases.

In general, the trend presented in Figure 7b clearly indicates distinct phases in the variation in radial permeability with the load (as reported by Bian et al. 2016 [21]).

First, permeability decreased with the increasing applied compressive loading (for all temperature levels). This phenomenon is attributed to the partial closure of heat-induced microcracks and

cracks (perpendicular to the load) caused by the increase in the applied compressive loading [21]. It appears between 0.6 and 5 MPa for the heating at 120 and 250 °C, between 0.6 and 2 MPa for 400 °C and between 0.6 and 0.9 for 600°C.

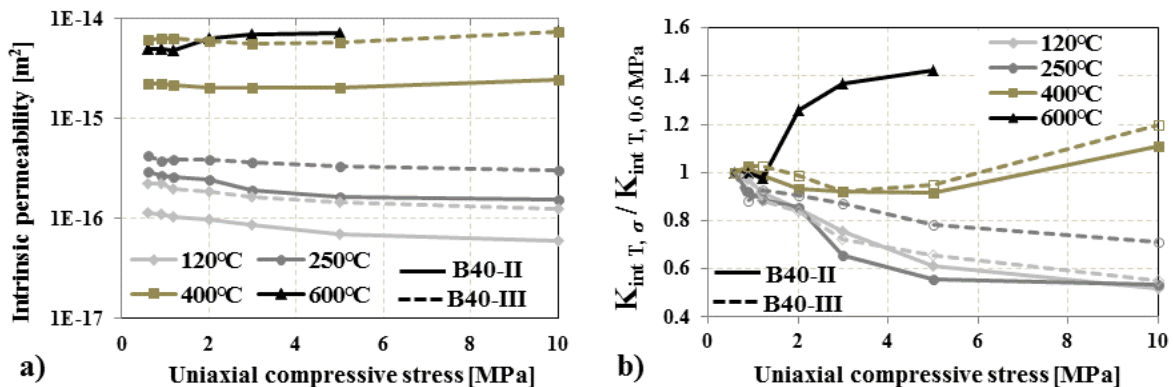


Figure 7 Effect of uniaxial compressive loading on the radial permeability of concretes.

Secondly, a very small change or even almost constant permeability was observed. In this phase, it is believed that there is a combination of crack initiation, crack growth, and crack closure [21]. This phase is observable up to 5 MPa for 120 and 250°C, between 2 and 5 MPa for 400°C, between 0.9 and 1.2 MPa for 600°C.

Finally, an increase in permeability was observed with the further increase of the compressive stress. At 120 and 250°C, the applied stress is not sufficient (10 MPa) to observe increase of permeability. For B40-II specimens heated at 400 and 600°C, the phenomenon is observed above 5 and 1.2 MPa, respectively (see Figure 7b). Almost similar behaviour was found for the B40-III preheated at 400°C, while the specimens preheated at 600°C were more damaged during heating, hence it was not possible to measure the permeability of these specimens due to very fast gas flow. The increasing permeability with increasing loads of this behaviour could be due to the extension of the existing cracks (i.e. remaining unclosed cracks) and creation and opening of new cracks [21] due to Poisson's effect (i.e. increase transversal deformation due to crack opening in the direction of the gas flow) and begin to join together in somehow, which make the permeability to reach the maximum in this phase. These observations are in good agreement with the ones of Bhanthia et al. 2005 [22]. Bhanthia et al. 2005 [22] found that a significant increase in radial permeability of plain concrete when the applied uniaxial stress was beyond $0.3f_u$ (where f_u is the strength in compression at 20°C).

As we have seen in Sections i and ii of part 3 (apparatus and test procedures), B40-II always exhibited lower permeability than B40-III in all the heating levels (see Figure 7a), which is really a good agreement among all the tests.

GENERAL DISCUSSION AND CONCLUSIONS

This research aimed to contribute determining the effect of loading on the gas permeability of concrete which is a key parameter of concrete fire spalling. Axial and radial gas permeability tests were carried out on two concretes, B40-II and B40-III, under different preheating and loading conditions.

From our results, it has been clearly shown that the presence of loading and their levels have a significant influence on the gas permeability of concrete.

Results from tests i) have shown that for all preheating temperatures, axial permeability decreases when confining pressure increases by reducing the width of the axial cracks.

In tests ii), samples were preheated under uniaxial compressive stress. This preconditioning induces the formation of cracks parallel to the direction of compressive stress. Tests results clearly show that axial permeability increases with uniaxial compressive stress applied during preheating.

In tests iii), radial permeability measurements were carried out on preheated samples under uniaxial compressive load. Curves determined at lower temperatures (120 and 250°C) show that permeability decreases when applied compressive stress increases. At the higher temperature, 600°C, the permeability decreases up to 1.2 MPa and then increases with the increase compressive stress. Curve determined at the intermediate temperature (400°C) first decreases, after that stabilises, and then increases. From the analyse of this curve, we propose that this finding arises from the combined effect and competition of both, closing of the cracks perpendicular to the load (permeability decrease) and the opening of the cracks parallel to the load (permeability increase).

As a result, permeability increases or decreases depending on the loading conditions and becomes anisotropic. Hence, the stress state, by governing the orientation and opening of the cracks is very important key factors which control the internal fluid transfer (i.e. permeability) and then directly triggers the build-up and magnitude of the pore pressure within the concrete structure. Stress state has then 2 major roles on concrete fire spalling: (1) a direct influence in the thermo mechanical mechanism and (2) an indirect influence in thermo-hydral mechanism by influencing the cracks opening and orientation and then, the permeability.

It was also found that the permeability of concrete made with CEM III cement (B40-III: 43% of slag) is higher than the one of concrete made with CEM II cement (B40-II: 3% slag) in all heating and loading conditions.

We have discussed the effects of loading on the residual permeability of specimen slowly heated in free mechanics conditions. The heating of the specimens creates some cracking principally due to thermal mismatch.

In the case of a structure submitted to a fire, the thermal gradients are much more important and the cracking of the structure is not only governed by the thermal mismatch. Nevertheless, the presence of a compressive stress and moreover a confining compressive stress reduces the risk of cracking and by the way increases the risk of spalling (see Miah et al. 2016 [2]).

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