Biographies

Djerbi Assia is a PhD Student at the Research Institute of Civil and Mechanical Engineering – IUT, Technical Institute of Saint-Nazaire - France. She is working on the influence of damage on mass transport in porous media.

Turcry Philippe is an Assistant Professor of Civil Engineering at the LEPTAB – "Laboratoire d'Etudes des Phénomènes de Transfert Appliqués au Bâtiment" of La Rochelle in France. His research interests are new building materials, such as self-compacting concrete and high performance concrete, and durability of cement-based materials.

Stéphanie Bonnet is an Assistant Professor of Civil Engineering at the Research Institute of Civil and Mechanical Engineering (GeM : UMR CNRS 6183). Her research interest is durability of concrete and particularly the aspect concerning the mass transport into concrete. She is starting also to study the maintenance and reliability of concrete structures exposed to marine environment.

Dr. Abdelhafid Khelidj is Professor of Civil Engineering at the Research Institute of Civil and Mechanical Engineering – IUT, Technical Institute of Saint-Nazaire - France. His research interests cover a broad spectrum in concrete materials and durability, such as heat and mass transfers within cement paste or concrete at early age, and Thermo-hydro-mechanical couplings in mature concrete.

INTRODUCTION

Transport properties of concrete are important and deserve thorough investigations as they significantly influence the durability of concrete. Water, carbon dioxide gas, and chloride ions are considered to be primal substances degrading the integrity of concrete structures as a result of their transport through and subsequent interaction with cement hydrates and embedded steel reinforcement. Extensive work has been carried on over the past decades to understand transport properties of concrete, and numerous service life prediction models have been introduced. The disadvantage of these models is that all predictions are carried out considering a perfect, uncracked concrete[1]. It appears that the extent to which the transport properties of concrete are modified by cracking greatly depends on the predominant transport mechanism. For example, the diffusivity of cracked concrete[2] was found to rise only by a factor between 1 and 10, while the increase in permeability can constitute severals orders of magnitude[3,4,5]. Olga[6] examined the effect of crack width and crack surface roughness on chloride ingress into conrete using chloride bulk diffusion test. The experimental result showed that the chloride diffusion in concrete containing the transecting crack becomes a case of two-dimensional diffusion as regarded with the crack widths used in this study.

The objective of this research was to examine the influence of crack width on gas permeability and chloride migration into concrete. Cracks of designed widths were induced in the concrete specimen using a controlled splitting tensile test. After loading intrinsic gas permeability was measured, using a constant head permeameter and chloride migration coefficient was evaluated by migration test in steady state conditions, in order to compare the influence of these transport properties into cracked concrete.

EXPERIMENTAL PROGRAM

Preparation of the samples

A high performance concrete was made (HPC), Concrete cylinders, ∅110 x 200 mm, were cast in two layers. Each layer was compacted by a mechanical vibrator. The cylindrical specimens were stored in a room maintained at 20°C and about 90% relative humidity (RH) for 24 hours after casting, and were cured in water at 20°C for 3 months. They were stored in air-conditioned room (20°C and RH 50 ± 5%) until testing. The characteristics of this concrete are shown in table 1.The porosity is found by saturating the concrete specimen with water. Concrete cylinders were cut using a diamond blade saw to obtain 50 mm-thick discs. Three were extracted from each cylinder for splitting tensil test. After cutting, these discs were sealed with two epoxy resin coats in order to ensure one-dimensional gas and chloride flow inside the discs.

Precracking of samples using controlled splitting test

Controlled splitting tests were used to induce cracks in the specimens. Diametrical loading (i.e. under Brazilian test configuration), is one of the methods for estimating the tensile stress of concrete through indirect tension. This stress mode is applied to the discs (110 mm in diameter and 50 mm in thickness). These discs can be diametrically loaded until obtaining a predetermined lateral displacement. Two LVDT sensors, with a range of 0.5 mm and a precision of 1 µm, were used to measure the diametrical displacement which is normal to the load axis along the two opposite faces of the disc. Their average was called lateral displacement or crack opening displacement[3,4] (COD). The sensors were maintained by two U-bolts clamped to the disc via screw-punch (see Fig 1). Each disc was subjected to 4 to 10 cycles, in order to obtain various lateral displacements under loading. The wanted maximum COD under loading is obtained during the measurement by considering as reference the previous COD, that is recorded 30 minutes after unloading (Fig 2). Imposed crack openings under loading were 50, 100, 200, 400 and 700 µm. The loading induced tensile stresses concentrated around the secant diameter with the loading plan. The damage is localized and a single crack crossing the disc is generally observed in this plan.

Gas permeability test procedure

Intrinsic permeability was measured using a Cembureau constant head permeameter with nitrogen as the neutral percolating gas[7]. The relative pressure ($P_i - P_{atm}$) applied to the sample ranged between 0.05 MPa and 0.3 MPa and was measured by a digital pressure gauge with a 100 Pa precision. Permeability measurements were made in an air-conditioned room (20 ± 1°C and RH 50 ± 5%). Each disc was tested with five differential pressures: 0.05, 0.1, 0.15, 0.2 and 0.3 MPa for uncracked specimen and with five differential pressures: 0.01, 0.015, 0.02, 0.025, 0.03 MPa for cracked specimen. The establishment of steady state flow before an actual measurement required a significant time (varying from 30 minutes to several hours). This condition was verified by taking two measurements separated by a 10 minutes interval. If two values differed by less than 2%, a steady state flow condition was assumed to be achieved. For each differential pressure, the apparent coefficient of permeability k_A (m²) is calculated from the Hagen-Poiseuille expression (Eq 1) for laminar flow of compressible viscous fluids through a porous body[3].

$$k_A = \frac{Q}{A}\frac{2\mu\ L\ P_{atm}}{(P_i^2 - P_{atm}^2)} \quad (1)$$

where L is the thickness of the sample (m), A is the cross-sectional area (m²), Q is the gas flow (m^3/s), μ is the coefficient of viscosity ($1.78.10^{-5}$ Pa.s for nitrogen gas at 20°C), P_i is the applied absolute pressure or inlet pressure (Pa), and P_{atm} is the atmospheric pressure (Pa).

In fact, the gas percolation through a fine porous body like concrete, can be regarded as resulting from two flow modes: viscous flow and slip flow or Knudsen flow. Various methods for the calculation of non-viscous flow exist. The most widely used is the relation proposed by Klinkenberg[8] (Eq 2) introducing the concept of an intrinsic coefficient of permeability k_V relative to viscous flow only.

$$k_A = k_V\left(1 + \frac{b}{P_m}\right) \quad (2)$$

where P_m is mean gas pressure, $P_m = (P_i + P_{atm})/2$, b is the Klinkenberg coefficient (Pa) which is function of the porous body and the infiltrated gas, and K_V is the limiting value of gas permeability when the mean pressure P_m tends towards infinity. The method of determination of k_V consists in measuring k_A at different pressures (P_i) and plotting it against the inverse of the mean pressure ($1/P_m$) (Fig 3). The slope of the line leads to the empirical Klinkenberg coefficient b.

Steady state migration testing

Since diffusion experiments are time-consuming, steady state migration tests were developed to accelerate chloride ions through the concrete[9,10,11]. Each specimen is placed between the two compartments of a cell where flat silicone circular seals ensure that the system is leaktight (Fig 4). The solutions were made with NaOH (0.025 mol/l) + KOH (0.083 mol/l) in upstream and downstream compartment. NaCl (0.513 mol/l) was added in the upstream solution. A 12 V was applied between the sides of the concrete sample and the test was carried out at T=20±5°C. The downstream solution was titrated with silver nitrate (0.01M). As the flux becomes constant, Nernst-Planck's relation[9] allows to deduce the value of the diffusion coefficient, as seen in Eq 3:

$$J(x,t) = -D_e\frac{\partial c(x,t)}{\partial x} + D_e\frac{FE}{RTL}c(x,t) + c(x,t)\nu(x) \quad (3)$$

where D_e is the effective migration coefficient of concrete (m²/s), c(x,t) is the chloride concentration of the upstream compartment ($mol.m^{-3}$) assumed to be constant, and J is the flux of chloride ions ($mol/(m^2.s)$), t is the time (s), F is the Faraday constant (F = 96480 $J.V^{-1}$), E is the actual potential drop between the surfaces of specimen (V), R is the gas constant ($R=8.3144\ J.mol^{-1}K^{-1}$), T is the absolute temperature (K), and ν(x) is the velocity of the solute (m/s).

If the concrete is saturated, the velocity of the solute can be neglected. Since the potential drop applied here is ≥ 10V, ions migrate as a result of the electrical field rather than of the concentration gradient. This insures that the diffusion flow can be neglected in the experiments as shown by Andrade[9]. Eq 3 can be simplified and then Eq 4 is obtained:

$$D_e = \frac{L}{c(x,t)} \frac{RT}{FE} J(x,t) \quad (4)$$

RESULTS AND DISCUSSION

Effect of splitting tensile stress

This test was carried on six high performance concrete discs. These discs were subjected to 4 to 10 cycles until various lateral displacements under loading of 50, 100, 200, 400, 700 μm were obtained. A crack was observed on both faces of the discs after unloading using a videomicroscope with 200 times magnification. The relationship between the crack recovery and the maximum crack opening displacement is shown in Fig 5. If the specimen was unloaded before 200 μm of lateral displacement under loading, the remaining crack opening displacement would be very small. As a result, the crack may show little effect on transfert properties of concrete.

Relationships between COD and relative increase in permeability

After unloading, the applied splitting tests can increase the initial permeability k_{v0} of uncracked concrete specimens by about four orders of magnitude. Fig 6 shows the relative increase of the permeability (i.e. the ratio $k_v(d)/k_{v0}$) versus the COD, where $k_v(d)$ is the global permeability of a damaged disc. Using the transport parallel model of concrete[3] described in Fig 7, $k_v(d)$ could be written with Eq 5.

$$k_v(d) = k_{v0} + k_v' \quad (5)$$

k_v' is the permeability in the crack for an impermeable media. This can be written with the following equation:

$$k_v' = \frac{\xi\, w^3}{\Delta 12} \quad (6)$$

The Eq 6 is derived from the parallel-plate theory commonly used in cracked rocks permeability[3], which assumes that cracks are represented by parallel plan with a width w and spaced by a distance Δ (m), ξ is the reduction factor comprising the roughness of cracks. Using Eq 5 and Eq 6 the relative increase in permeability can be expressed as:

$$\frac{k_v(d)}{k_{v0}} = 1 + \frac{\xi}{k_{v0}\Delta} \frac{(\gamma COD)^3}{12} \quad (7)$$

An empirical factor γ is introduced in order to estimate the main crack width, w, from the measured COD. From the main crack width measured using the videomicroscope and the recorded COD after unloading, this factor can be ajusted to a value equal to 0.5 for all concrete type discs and Δ is determined to be 0.1.

A polynomial regression was then carried out by assuming the relationship given in Eq 7. The Fitted parameter is F, with $F = \xi\, \gamma^3$. The adjustment between the relative increase in permeability measured and the model is given in Fig 6. The values of the correcting factor ξ can be evaluated from the adjusted value of γ (2nd row of Table 2) or from the average width measurements of the main crack by videomicroscope w using the relationship given in Eq 6 (3^{rd} row of the Table 2). The values ξ obtained are almost the same.

Steady state migration test

The chloride migration of these cracked discs was measured perpendiculary to plane faces. Transfer properties in other direction have been different[6]. The variation over time in the quantity of chloride ions in the downstream cell is shown in Fig 8. The chloride migration rate (dC/dt, proportional to D_e) of cracked samples increased with increasing crack width. Time to penetrate through the specimen t_{lag} was reduced from 72 hours for uncracked concrete to 0 hours for the most cracked concrete (Table 3).

Fig 9 shows the relationship between the open area of transecting cracks and migration coefficient. This last is increasing by a factor of about 3.5 for the most cracked concrete by comparing to the coefficient of uncracked specimen. The migration coefficients obtained from these experiments will be compared with the model of transport in parallel. This model could be described in Fig 7 and with the following Eq 8:

$$A\ J^{'}\left(L,t\right)=A\ J_0\left(L,t\right)+A_cJ_c\left(L,t\right) \tag{8}$$

where A, A_c, are the specimen area and the crack area respectively, $J^{'}(L,t)$ is the flux with in the cracked specimen, $J_0(L,t)$ is the flux with in the uncracked specimen and $J_c(L,t)$ is the flux in the crack. Then the migration coefficient in the crack $D_c = 1.59\ 10^{-9} m^2/s$ was obtained using Eq 9 and the linear relationship obtained in Fig 9.

$$D_e^{'}(d)=\frac{A_cD_c}{A}+D_{e0} \tag{9}$$

where $D_e^{'}(d)$ is the migration coefficient in cracked specimen and D_{e0} is the migration coefficient in uncracked specimen. This result confirms the validity of the model of transfer in parallel.

Numerical simulations of this model were carried out by combining Eq 3 and the continuity equation written as following:

$$p\frac{\partial c(x,t)}{\partial t}=-\frac{\partial J(x,t)}{\partial x} \tag{10}$$

where p is the concrete porosity. In this study, interactions between chloride ions and concrete were neglected. Using Eq 3 and Eq 10, the migration problem can expressed as:

$$\frac{\partial c(x,t)}{\partial t}=\frac{D_e}{p}\left[\frac{\partial^2 c(x,t)}{\partial x^2}-\frac{FE}{RT}c(x,t)\right] \tag{11}$$

The flux within the crack $J_c(x,t)$ and the migration equation problem within the crack can be written in the same manner:

$$J_c(x,t)=-D_c\frac{\partial c_c(x,t)}{\partial x}+D_c\frac{FE}{RT}c_c(x,t) \tag{12}$$

$$\frac{\partial c_c(x,t)}{\partial t}=D_c\left[\frac{\partial^2 c_c(x,t)}{\partial x^2}-\frac{FE}{RT}c_c(x,t)\right] \tag{13}$$

where $c_c(x,t)$ is the ions concentration in the crack. Eq 11 and 13 were solved using finite differences with an implicit scheme (in order to avoid numerical instabilities). The limit conditions are: c(0,t)=0.5 mol/l and c(L,t)=0 mol/l. The cumulative ions quantity in the downstream compartment is obtained by time integration of $J_t(L,t)$ (Eq 8). Figure 10 shows the comparison of the numerical simulations and the measurements for various crack areas. In spite of the relative simplicity of the parallel model, simulations are in good agreement with measurements.

Comparison between intrinsic permeability and migration coefficient

The comparison between chloride migration coefficient and gas permeability was investigated in cracked concrete Fig 11. The chloride migration coefficient was measured on saturated concrete specimens while the gas permeability was determined on dry concrete specimens. These results indicate the gas permeability to be significantly more sensitive than chloride migration at last before the value of 2.54 mm^2 for crack area.

CONCLUSIONS

In this study controlled splitting tests were performed to obtain a series of concrete specimens with different crack widths. The results indicate the relationship between the crack recovery and the maximum crack opening displacement.
Gas permeability of concrete with different crack widths was evaluated. The results suggest that permeability increases with COD cubed, as shown in theoretical models of cracked rocks. A parameter γ, accounting the tensile crack density and the crack-width distribution was introduced to estimate the reduction factor ξ. The value of this factor is 0.028.

The chloride migration coefficient was determined on cracked concrete using steady state migration test. The results indicate that the chloride migration coefficient increased with increasing crack width and the time to penetrate through the specimen was reduced which is very important to evaluate the initiation corrosion. A relationship was found between chloride migration coefficient and the open area of transecting cracks and a good comparison was obtained between measured values and numerical simulations. The analysis of the results confirms the validity of the model of transfer in parallel.

A comparison was given between the gas permeability and chloride migration coefficient. The result showed that the gas permeability was significantly more sensitive than chloride migration with respect to the crack widths used in this study. This can be explained from the theoretical models that show that the rate flow of gas through cracked concrete is proportional to the cube of the crack width, whereas the chloride migration coefficient through cracked concrete is shown to be proportional to the crack area. The different relationships obtained in this study have to be checked with other concretes.

ACKNOWLEDGMENT

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Table 1 — Concrete characteristics

Mix ingredients	HPC (kg/m^3)
Coarse aggregate, 12.5 – 20 mm	777
Medium aggregate, 4 – 12.5 mm	415
Sand (Boulonnais), 0 – 5 mm	372
Sand (Seine), 0 – 4 mm	372
Ciment CPA-CEM I 52.Lafarge	353
Total water	172
w/c ratio	0.49
28-d compressive strengh	54 MPa
90-d compressive strengh	65 MPa
28-d porosity by water saturation	10.91

Table 2 — Fitted parameter, F, and determinations of the reducing factor ξ

	HPC
$F=\xi\gamma^3$	$3.8.10^{-3}$
ξ value if $\gamma = 0.5$	0.030
ξ value determined from the main crack width w measurement	0.027

Table 3 — Effect of concrete damaging on time lag

COD (µm) After loading	t_{lag} (hour)
0	72.38
15.76	63.41
37.06	57.76
100.16	56.89
200.88	27.83
390.40	0

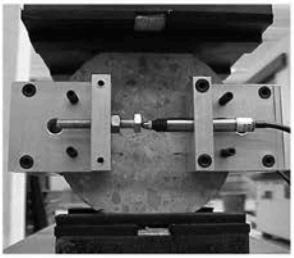

Fig. 1 — Controlled splitting test

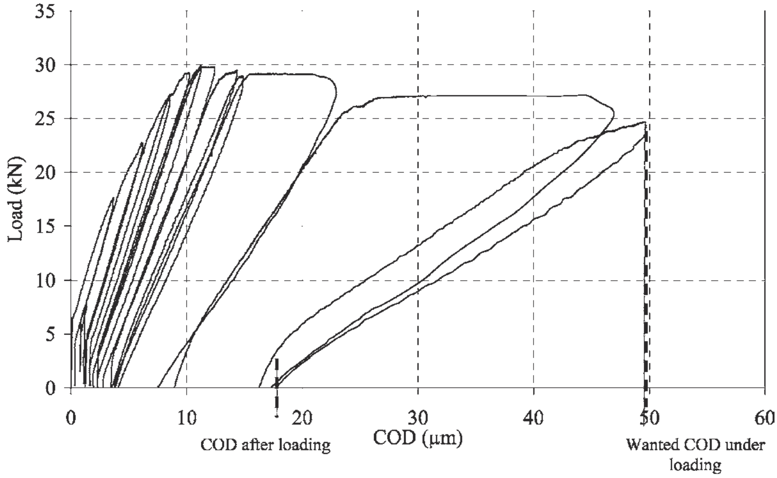

Fig. 2 — Typical splitting tensile load-COD curve

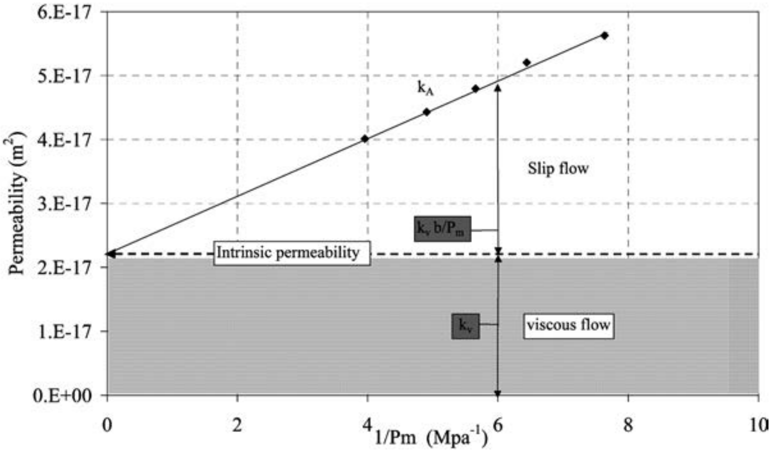

Fig. 3 — Determination of k_v from the measurements of k_A for different inlet pressures

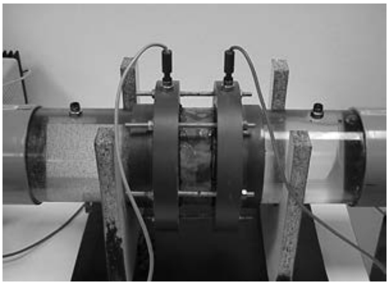

Fig. 4 — Migration Cell

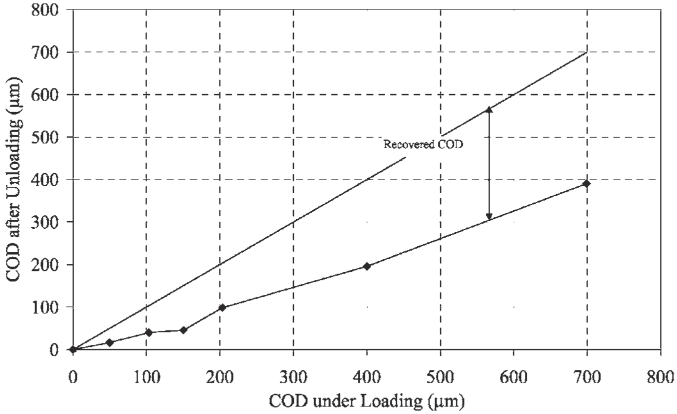

Fig. 5 — Recovery of crack opening displacement (COD) after unloading

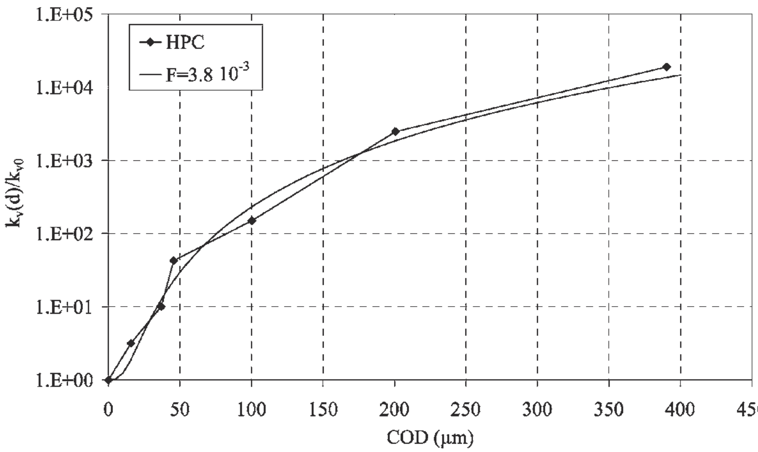

Fig. 6 — Relative increase in permeability versus COD after unloading

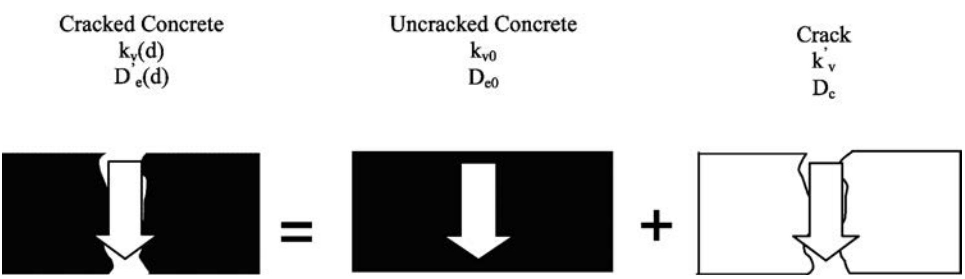

Fig. 7 — Transport parallel model of concrete