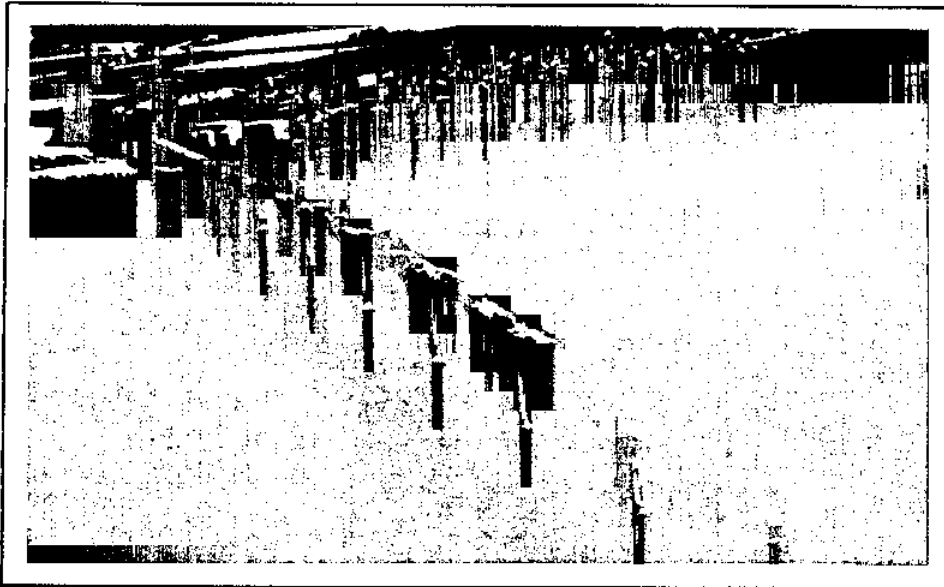


# Mario Collepari Symposium

on

## *Advances in Concrete Science and Technology*



### Determination of Chloride Binding Isotherms from Migration Tests

J.P. Ollivier, J. Arsenault, O.Truc et J. Marchand.

**Synopsis:** In the present paper we propose a new method to determine the chloride binding capacity from a migration test in concrete. In our investigation we conducted four different migration tests where all series were carried at a fixed potential of 10 volts. Four different chloride concentrations were tested:  $c_2 = 5, 10, 20$  and  $30$  g/L. We also performed five migration tests with different applied potentials to evaluate the influence of the electrical field on the chloride binding mechanisms. The different series were carried out at:  $2, 5, 10, 20$  and  $30$  volts. In all series, the chloride concentration  $c_2$  of the upstream compartment was set at  $20$  g/L. Results show that, for a range of  $2$  to  $30$  volts, the applied potential does not seem to influence the chloride binding capacity, and results for the material tested for different chloride concentrations clearly shows that the binding capacity is not a linear function. From these migration tests, it is also possible to establish the influence of the concentration on the migration coefficients.

**Keywords:** Chloride penetration, diffusion process, chloride binding isotherms, migration test, electrical field.

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Editor

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## INTRODUCTION

During their service life, concrete structures can be exposed to various types of aggression. In most cases, the deterioration mechanisms involve the transport of ions through the material pore structure. In that respect, the reliable prediction of the service life of the structure requires a sound understanding of the mechanisms of ion penetration in cement-based materials.

This is particularly the case for reinforced concrete structures directly exposed to chloride ions. Over the past decades, numerous surveys have clearly indicated that chloride ions, originating from deicing salts or sea water, are the primary cause of reinforcing steel corrosion (1-3). The chloride ions that have penetrated through the concrete cover depassivate the oxide film covering the reinforcing steel and accelerate the corrosion reaction. Chloride ions are also known to significantly increase the salt scaling deterioration of concrete surfaces (4).

## METHOD

### Chloride Penetration in Concrete

Under natural exposure conditions, various mass transport processes can account for the penetration of chloride ions through the concrete pore structure. When the degree of saturation of the concrete is above a certain critical level, chlorides can be transported by simple diffusion process. Under unsaturated conditions, chlorides can penetrate by capillary suction. For concrete elements exposed in a splash zone, chlorides can even be transported by a permeation process. Although capillary absorption and permeation can, in certain cases, be of significant importance, studies indicate that chlorides are mainly transported through the concrete pore network and microcracks by a diffusion process.

Over the past decade, the diffusion of chlorides in cement-based materials has been the subject of a great deal of interest. Most of the papers recently published on the subject have clearly emphasized the complexity of this phenomenon (1, 5-7). Aware or not of the intricate nature of the chloride diffusion process, many authors have relied on Fick's first law to express the relationship between the flow of chlorides through the concrete pore network and the concentration gradient in the solution:

$$F = -D_c \frac{\partial c}{\partial x} \quad [1]$$

The conservation law applied to a concrete element allows us to express Fick's second law:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} \left( D_c \frac{\partial c}{\partial x} \right) = D_{F2} \frac{\partial^2 c}{\partial x^2} \quad [2]$$

This validity of these equations rests on two assumptions:

- the diffusion coefficient  $D_c$  is assumed to be constant throughout the material, i.e. that the diffusion coefficient is totally independent of the ion concentration. If this assumption is valid, the diffusion coefficient  $D_{F2}$  is a constant and can be linked to the effective diffusion coefficient by the following expression:  $D_{F2} = \frac{D_c}{p}$  where  $p$  is the water porosity of the material;
- it is also assumed that, upon the penetration process, chloride ions do not interact, in any way, with the hydrated cement paste.

If both assumptions are valid<sup>1</sup>, the solution of equation [2] can be found analytically using a LAPLACE transform and knowing the boundary conditions. For a specimen fully immersed in a solution of concentration  $c_1$  and for which the initial concentration is equal to  $c_0$ , the solution of equation [2] yields:

$$c(x, t) = c_1 + (c_1 - c_0) \left[ 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{D_s t}} \right) \right] \quad [3]$$

<sup>1</sup> These assumptions are valid for most molecular diffusion processes in free liquids and for molecular diffusion processes in some porous media. Both assumptions are however only valid for diffusion processes in ideal solutions.

Assuming the validity of equation [2], many authors have developed various models to predict the penetration of chlorides in concrete structures (1, 8, 9). In most cases, the prediction of the chloride penetration is a three-step process which includes:

- the determination the chloride ion profile for a sample which had been immersed in a salt solution of known concentration;
- the calculation of the diffusion coefficient  $D_{F2}$  using a curve fitting technique;
- the prediction of the chloride penetration on the basis of equation [3].

Unfortunately, the validity of the assumptions at the basis of equations [2] and [3] is not verified for ionic diffusion processes in porous media. For instance, there exists an overwhelming body of experimental data that shows that ionic diffusion is a concentration-dependent phenomenon. Over the years, numerous studies have also clearly indicated that chlorides can strongly interact with the hydrated cement paste (1, 10-13). The interaction can be both chemical and physical in nature. For instance, chlorides can react with the unhydrated aluminates phases to form new compounds such as calcium monochloroaluminates (or FRIEDEL's salt), calcium trichloroaluminates and chloroferrite hydrates (10, 11). Numerous studies have also clearly established that chlorides can physically interact with the calcium silicate hydrates (10-13).

The amount of bound chlorides has been found to be directly influenced by a number of parameters such as (1, 2, 12, 13):

- the free chloride concentration of the pore solution;
- the amount of binder;
- the specific surface of the hydrated cement paste.

The chloride binding mechanisms can also be affected by numerous other parameters such as (1, 2, 12, 13):

- the type and the concentration of ions in solution;
- the ambient temperature;
- the type of binder and its composition (e.g. supplementary cementing materials);
- the type of aggregate;
- carbonation.

The effect of the hydrated cement paste binding capacity on the diffusion of chlorides has been discussed in many recent publications (5, 6, 14, 15). The strong interaction of chlorides with the hydrated cement paste contributes to significantly reduce the rate of penetration. In practice, the binding process can be described by an "interaction isotherm" which gives the variation of bound chlorides as a function of the concentration of free chlorides in the pore solution. Once the interaction isotherm is experimentally determined, equation [2] can be modified to account for the binding process:

$$\frac{\partial c}{\partial t} = \frac{D_c}{\rho + (1-\rho)\rho_s} \frac{\partial^2 c}{\partial x^2} \quad [4]$$

where  $\frac{\partial C_b}{\partial c}$  represent the slope of the isotherm and  $\rho_s$  is the concrete bulk density. The bound chloride concentration  $C_b$  is usually expressed on a unit mass of dry paste basis and the free chloride concentration  $c$  is expressed on a unit volume of solution basis. If the interaction isotherm is linear, the Fick's second law can be expressed as equation [5]:

$$\frac{\partial c}{\partial t} = D_a \frac{\partial^2 c}{\partial x^2} \quad [5]$$

where the coefficient ( $D_a$ ) is called the apparent diffusion coefficient. The value of the apparent diffusion coefficient is a constant only if the effective diffusion coefficient is constant and the interaction isotherm is linear. In that case, the apparent diffusion coefficient is similar to the  $D_{F2}$  coefficient appearing in equation [2].

Many recent investigations have indicated that the binding of chlorides by the hydrated cement paste is a non-linear process (12, 13, 16). The non-linearity of the binding process greatly complicates the mathematical treatment of equation [4] which cannot be solved analytically. To resolve this equation, one has to rely on numerical methods.

Figure 1 shows the influence of the non-linear binding process on the penetration of chloride in a concrete structure after 60 years of immersion. the concrete was initially free of chlorides and the diffusion coefficient was assumed to be equal to  $10^{-12} \text{ m}^2/\text{s}$ .

Chloride binding isotherms can be experimentally determined in various ways (6):

- by dissolving a given amount of chlorides to the mix water. After a certain curing period, the pore solution is extracted using a pore pressure technique and the chloride concentration is measured. This technique has been found to greatly overestimate the amount of "free" chlorides (17, 18);
- by immersing a thin specimen of concrete in a chloride solution of known concentration. Once the equilibrium between the solid and the solution is reached, the total amount of chlorides present in the specimen can be measured by usual techniques;
- by immersing a specimen of crushed concrete in a chloride solution of known concentration. Once the equilibrium between the solid and the solution is reached, the residual concentration of chlorides in solution is measured. The amount of bound chlorides is calculated on the basis of the difference between the initial and final chloride concentration of the solution (11, 12).

When compared to the first procedure, the last two methods present the net advantage of being more representative of natural exposure conditions. In practice, chlorides are rarely present in significant amount in the mix water. Concrete structures are usually exposed to chlorides after a minimal curing period during which the material has benefited from a certain hydration.

However, the main drawback of the last two methods is that they cannot take into account some of the particular features of the concrete microstructure. For instance, the influence of microcracks on the chloride binding mechanisms can hardly be assessed with these two methods. The other disadvantage of these methods is that the amount of bound chlorides and the shape of the isotherms is strongly affected by the type and the concentration of companion ions in solution.

In order to overcome these problems, an improved method was recently developed by Bigas et al. (19). This new method is however time-consuming, and, in practice, limited to mortar samples. In the following section, we present an accelerated method to determine the chloride binding isotherm. This new method has been developed on the basis of a steady-state chloride migration test and is adapted to the testing of concrete samples.

## Presentation of the New Method

### Description of the Steady-State Migration Test

The determination of the chloride transport properties by a diffusion test is often a time-consuming process. Since diffusion tests generally tend to last several months, numerous attempts to design accelerated test procedures have been made. In most cases, the transport of ions through the samples is accelerated by applying an electrical potential to the system.

The various accelerated test procedures can be divided in three categories. In certain tests, the rate of ion migration through the sample is monitored for a few weeks, and a migration coefficient is calculated. In the following paragraphs, these procedures will be referred to as steady-state migration tests. In non-steady state migration tests, the depth of ion penetration within the sample is measured after a certain testing period. Finally, in conduction tests, the total electrical charge passing through the sample over a short period is measured. In this respect, the well-known rapid chloride permeability test can be considered as a conduction test.

As previously mentioned, the new method has been developed on the basis of a steady-state migration test that is usually performed to assess the chloride transport properties of a concrete sample. As can be seen in Figure 2, the experimental set-up used for the migration test is very similar to a simple diffusion cell. A concrete sample is placed at the center portion of the cell between two compartments. The upstream compartment contains a hydroxide solution (often NaOH + KOH) in which a certain amount of a chloride-based salt has been dissolved. The downstream is filled with the hydroxide solution free of any chlorides. As will be discussed in the following paragraphs, the selection of the upstream and downstream solutions is important, and may have a strong influence on test results.

As shown in Figure 2, an external D.C. potential is applied to the cell in order to accelerate the transport of chloride ions through the sample. The positive electrode (anode) is placed in the downstream compartment while the negative electrode (cathode) is placed in the upstream compartment.

As can be seen in Figure 3, once the external potential is applied on the system, the chloride ions will start to migrate from the upstream compartment to the other side of the cell. The time required by the chloride ions to go through the concrete sample is known as the unsteady-state regime. After a certain period, the flow of chloride is rapidly stabilized and a steady state flow is reached.

In a steady-state migration test, the flow of chloride passing through the sample can be calculated on the basis of the Nernst-Planck relation (20):

$$\bar{J} = -D_c \left( \text{grad } c - zc \frac{F}{RT} \text{grad } \psi \right) \quad [6]$$

where  $z$  is the valence of the ion,  $\text{grad } \psi$ , the applied electrical field and  $F$  is the Faraday constant.

On the basis of a certain number of reasonable assumptions, the solution of equation (6) is given by :

$$J = D_c \frac{zF\Delta\psi \left[ c_1 \exp\left(\frac{zF\Delta\psi}{RT}\right) - c_2 \right]}{RTL \left[ \exp\left(\frac{zF\Delta\psi}{RT}\right) - 1 \right]} \quad [7]$$

where  $L$  is the thickness of the sample,  $c_1$  the chloride concentration in the upstream compartment (at  $x = 0$ ) and  $c_2$  the chloride concentration in the downstream compartment (at  $x = L$ ). If the applied electrical potential  $|\Delta\psi|$  on the system is strong enough, i.e. larger than 10 Volt, equation (7) can be simplified to:

$$J = D_c \frac{zF\Delta\psi c_1}{RTL} = M \frac{zF\Delta\psi c_1}{RTL} \quad [8]$$

Equation (8) can be used to calculate the effective migration coefficient.

#### Quantification of the Interactions on the Basis of the Steady-State Migration Experiment

Assuming an unidirectional flow along the  $x$  axis and noting  $U$  as the electro-chemical potential gradient across the sample, equation (6) can be modified as follows :

$$J = -D_c \left( \frac{\partial c}{\partial x} - \frac{zFU}{RTL} c \right) \quad [9]$$

by noting that

$$a = \frac{zFU}{RTL}$$

and integrating the constant flow (during the steady-state regime between the boundaries of sample, one finds that:

$$c(x) = \frac{c_1 e^{aL} - c_2 - e^{ax} (c_1 - c_2)}{e^{aL} - 1} \quad [10]$$

Assuming that  $c_2 = 0$ , it can be easily seen that :

$$c(x) = c_1 \frac{e^{aL} - e^{ax}}{e^{aL} - 1} \quad [11]$$

The distribution of free chlorides within the concrete sample can be described by the  $c(x/L)$  function which is related to the electro-chemical potential gradient  $U$ . As can be seen in Figure 4, if the electro-chemical potential gradient is high enough, the free chloride concentration distribution is a constant throughout the sample once the steady-state regime is established.

Profile (1) given in the figure 4 corresponds to the experimental conditions of the accelerated test described in this paper but, for an DC potential of 2 Volt. Profile (2) in the same figure corresponds to an experiment leaded with a very low applied potential ( $U=0,5$ Volt).

Hence it is possible to determine the amount of bound and free chlorides from a migration test. Since, upon the steady-state regime, chlorides are uniformly distributed throughout the specimen, it is possible to analyse a few grams of material obtained by crushing the middle portion of the sample.

Chloride can be extracted by nitric acid and their concentration determined by a potentiometric method. The mass of total chloride,  $C'_T$ , can therefore be expressed on a unit mass of sample basis. Assuming that the material porosity is totally filled with the pore solution (which has a density  $\rho_c$ ), the mass of chloride  $C_T$  can also be calculated on a unit mass of solid basis using the following equation:

$$C_T = C'_T \left( 1 + \frac{\rho_c}{\rho_s} \frac{p}{1-p} \right) \quad [12]$$

The amount of free chlorides obtained by a water extraction can also be determined using a potentiometric method. As for the amount of total chlorides, the mass of free chloride obtained by this method is expressed on a unit mass of sample basis. The mass of free chlorides expressed on a unit mass of solid basis ( $C_F$ ) can be calculated using the following relation:

$$C_F = C'_F \left( 1 + \frac{\rho_c}{\rho_s} \frac{p}{1-p} \right) \quad [13]$$

The amount of bound chloride,  $C_b$ , expressed on a unit mass of solid basis can finally be calculated by equation (14):

$$C_b = C_T - C_F = (C'_T - C'_F) \left[ 1 + \frac{\rho_c}{\rho_s} \frac{p}{1-p} \right] \quad [14]$$

$C_F$  can also be established by assuming that the amount of free chlorides within the sample is equal to  $c_1$ , the chloride concentration in the upstream compartment. Assuming that the electro-chemical potential gradient applied to the system is sufficient, the concentration in free chlorides can be obtained using on equation [11]. If  $c_1$  is expressed on a unit mass of solid one can derive the following equation:

$$C_F = \frac{c_1}{\rho_c + \rho_s \frac{1-p}{p}} = \frac{c_1}{\rho_c + \rho_s \frac{1-p}{p}} \quad [15]$$

The amount of bound chloride  $C_b$  can therefore be calculated using equation [14]. This concentration corresponds to a free chloride concentration  $c_F$ . The set of ( $C_b$ ,  $c_F$ ) data corresponds to a point of the binding isotherm.

It is possible to determine the complete binding isotherm for a given material by repeating the migration test for different chloride concentrations. The main advantage of this procedure is that it provides the binding isotherm for a bulk sample. This procedure should also yield information on the influence of the chloride concentration on the migration coefficient. In the following paragraphs, an application of the method is given for a set of mortar samples.

## RESULTS

### Materials

The mortar mixture tested in this project was prepared with an ordinary portland cement (CPA-CEM I 52,5HTS). The chemical composition of the cement is given in Table 1. The mortar was prepared with a siliceous sand. The mortar mixture proportions are given in Table 2.

### Sample Preparation

Mortar cylinders (approximately 220 mm long x 110 mm in diameter) were cast according to the requirements of the French standard NF P 18.404. The cylinders were wet cured for 24 hours in a moist controlled room at 20°C before being removed from their mold. They were then immersed in a lime saturated solution until they were cut in 15 mm slices for testing.

### Steady-State Migration Test Set-Up

The test set-up used for this series of experiments is shown in Figure 2. The upstream compartment (compartment 1) and the downstream compartment (compartment 2) were filled with a [0,025 mol/L] NaOH and [0,082 mol/L] KOH solution. This solution is believed to have a chemical composition similar to that of the pore solution of the mortar. A certain amount of NaCl was dissolved in the upstream compartment prior to testing.

During the migration test, the chloride concentration in the upstream compartment was maintained constant by regularly renewing the solution. The amount of chlorides in the downstream compartment was regularly measured in order to calculate the flow of chloride throughout the sample during the steady state regime. In order to keep the boundary conditions as stable as possible, the solution in the downstream compartment was also regularly changed.

A 10-Volt DC potential was applied on the system through platinum and graphite grid electrodes. The electro-chemical potential gradient used in equation [8] is the one which is developed from one surface of the sample to another. In the calculations, one should not therefore use the nominal potential applied at each end of the cell. Despite its high ionic concentration, the test solution provides some electrical resistance and the real gradient across the sample is somewhat lower than the nominal potential. As can be seen in Figure 5, the evolution of the chloride concentration in both compartments does not significantly influence the conductivity of the test solutions.

### Experimental Program

The experimental program had two objectives:

- to evaluate the influence of the electrical field on the chloride binding mechanisms. Five migration test series were performed. In all series, the chloride concentration  $c_1$  of the upstream compartment was fixed at 20 g/L. The different series were carried out at: 2, 5, 10, 20 et 30 Volt .
- to determine the binding isotherm of the mortar mixture. To achieve this goal, we performed four different migration test series. All series were carried at a fixed potential of 10 Volt. The four different chloride concentrations tested were:  $c_1 = 5, 10, 20$  and 30 g/L.

Once the steady-state flow was established, the total and free chloride concentrations were measured on various slices of the test sample.

### Experimental Results

#### *Influence of the Electrical Field on Binding*

Once the steady state conditions had been achieved, the migration experiment was stopped. For each sample, free  $C'_F$  and bound  $C'_B$  chloride concentrations were measured on powdered samples taken at various depths within the mortar discs.

Figure 6 shows some experimental data obtained from two experiments carried out at 2 and 5 Volt respectively. As can be seen, the profiles in free and bound chlorides obtained for the experiment performed at 2 Volt tend to be pretty constant throughout the sample. Small variations can however be seen near the surface of the sample. For the experiment carried out at 5 Volt, no variation in the free and bound chloride concentrations can be observed. These results validate the assumptions at the basis of the derivation of equation [11] and allow us to quantify the interactions using the mathematical treatment previously described.

The bound chloride concentration of each powdered sample can be calculated using equation [14]. The amount of bound chlorides is the mean value of all the measurements made for one disc. Figure 7 shows the influence of the electro-chemical potential gradient on the interactions.

As can be seen, the interactions do not seem to be significantly influenced by the applied potential for values between 1 et 20 V/cm. Since the chloride concentration remains constant throughout the sample, chloride concentration determinations can therefore be limited to one single powdered sample taken from the center portion of each disc.

Free chloride concentration,  $C'_F$ , can also be determined by assuming that the chloride concentration of the pore solution is equal to the chloride concentration  $c_1$  of the upstream compartment.  $C'_F$  can be calculated using equation [15] assuming that the water porosity of the mortar is equal to 0,193 and a bulk density,  $r_s$  is equal to 2.56 g/cm<sup>3</sup>. The values of  $C_B$  can then be calculated using equation [14]. Both series of results are compared in Table 3.

As can be seen, results based on the assumption that the chloride concentration of the pore solution is equal to the chloride concentration  $c_1$  of the upstream compartment seem more dispersed. This dispersion may be explained by a lack of precision in measuring the water porosity of the material.

The previous series of tests can also provide information on the influence of the applied potential on the migration coefficients. Table 3 summarizes the results from our investigation. The results are also plotted in Figure 8.

Test results indicate an increase of the migration coefficient with an increase of the external potential. These results tend to confirm the data reported by McGrath and Hooton (21). No hypothesis has been proposed to explain this relationship, but we should not forget that the calculation of the migration coefficient from equation [8] depends on many assumptions (neglecting the diffusion process, considering a diluted solution, etc.). In order to validate the measurement of the effective diffusion coefficient, it will be necessary to identify the reasons behind this phenomenon.

#### *Binding Isotherms from a Migration Test*

Another migration test was conducted in order to determine the binding isotherm. Total chloride concentration was measured on crushed sample of mortar taken from the center portion of the sample. Results are shown in Table 4 and the resulting binding isotherm is given in Figure 9. The binding isotherm in figure 9 clearly shows that the binding capacity is not a linear function.

From these migration tests conducted using different chloride concentrations, it is also possible to establish the influence of the concentration on the migration coefficients. Figure 10 illustrates the influence of chloride concentration on the migration coefficient.

### CONCLUSION

- The chloride concentration front remains constant throughout for a DC potential over two volts;
- The potential does not influence significantly interactions between chlorides and hydrated cement based material;
- Results from migration tests seem very interesting to define the interaction isotherm for a given material. We observe a little difference between the quantities of bound chlorides from migration test and from the method where we crush the sample. But we can think that the isotherm defined on powdered sample overestimates the bound chloride because the crushed specimen offers a bigger specific surface and thus a higher contact surface with the salt solution. Some diffusion tests for different chloride concentrations are underway with the aim of comparing the bound chlorides from both diffusion and migration tests;

- From migration we can also study the influence of the chloride concentration on the migration coefficient.

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Table 1. Chemical analysis of cement

Constituents	Proportion
SiO <sub>2</sub> (%)	22,80
Al <sub>2</sub> O <sub>3</sub> (%)	2,79
Fe <sub>2</sub> O <sub>3</sub> (%)	2,06
CaO (%)	66,95
MgO (%)	0,98
K <sub>2</sub> O (%)	0,26
Na <sub>2</sub> O (%)	0,31
TiO <sub>2</sub> (%)	0,15

Table 2. Mixture proportions of the mortar (w/c = 0,50)

Constituents	Proportion
cement (kg/m <sup>3</sup> )	450
water (kg/m <sup>3</sup> )	225
sand (kg/m <sup>3</sup> )	1350

Table 3. Results of chloride binding and migration coefficient for different applied potentials

N° sample	1	2	3	4	5	6	7	8	9	10
Applied potential (V)	2	2	5	5	10	10	20	20	30	30
Thickness (cm)	1.5	1.5	1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.6
Upstream cell concentration c <sub>1</sub> (g/L)	22.67	22.67	21.44	21.44	21.5	22.5	27.81	27.81	25.13	25.13
C <sub>b</sub> (mg/g dry mortar), from (14) et (15)	1.35	1.16	1.66	1.61	1.50	0.55	0.63	0.77	2.01	1.75
C <sub>b</sub> (mg/g dry mortar), from (13) et (14)	.069	0.58	0.59	0.44	0.69	0.69	0.49	0.44	0.59	0.66
M (10 <sup>-12</sup> m <sup>2</sup> /s)	2.06	2.50	2.36	2.88	3.0	3.07	4.22	3.91	4.54	4.42

Table 4. Chloride binding for different chloride concentrations

N° sample	L (mm)	c <sub>1</sub> (g/L)	C <sub>F</sub> (mg/g mortar)	C <sub>T</sub> (mg/g mortar)	C <sub>b</sub> (mg/g mortar)
M1_1	28.7	0.94	0.65	0.97	0.32
M1_2	17	6.2	1.33	1.37	0.56
M1_3	16.3	10.2	2.08	1.88	0.65
M1_4	17.5	11	2.26	1.99	0.64
M1_5	17.5	21.5	2.59	1.5	0.69
M1_6	28.8	22.5	1.73	0.5	0.69
M1_7	17.3	29.6	3.70	2.0	0.79

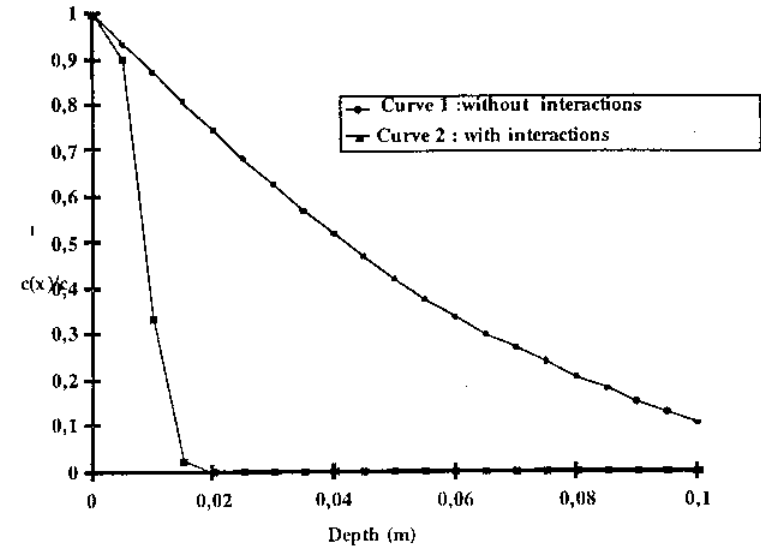


Fig.1: Theoretical distribution of total chloride in concrete, first taking into consideration interactions then without interactions in the transport process.

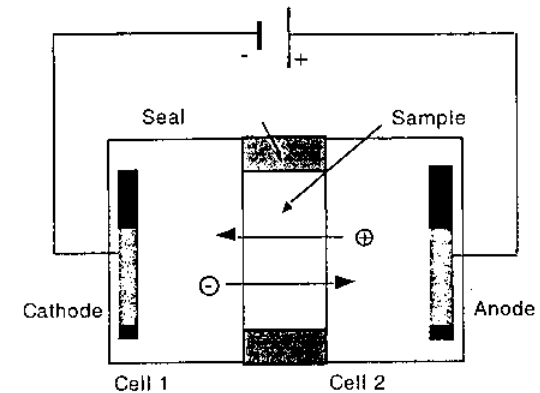


Fig. 2: Illustration of the migration test set-up

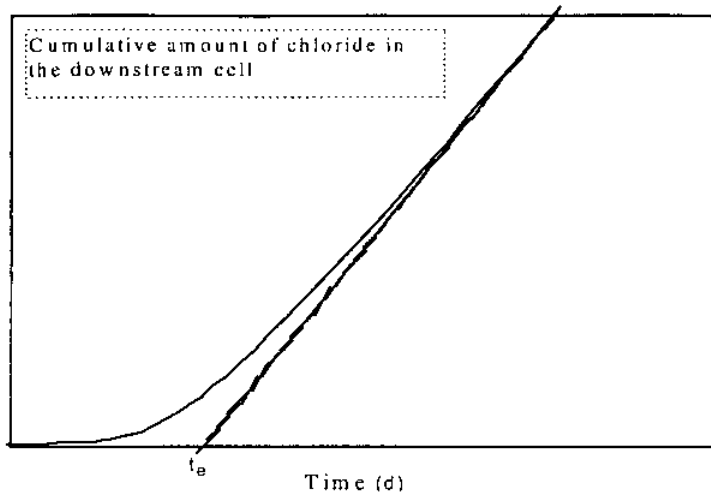


Fig. 3: Cumulative amount of chloride passing through the concrete sample

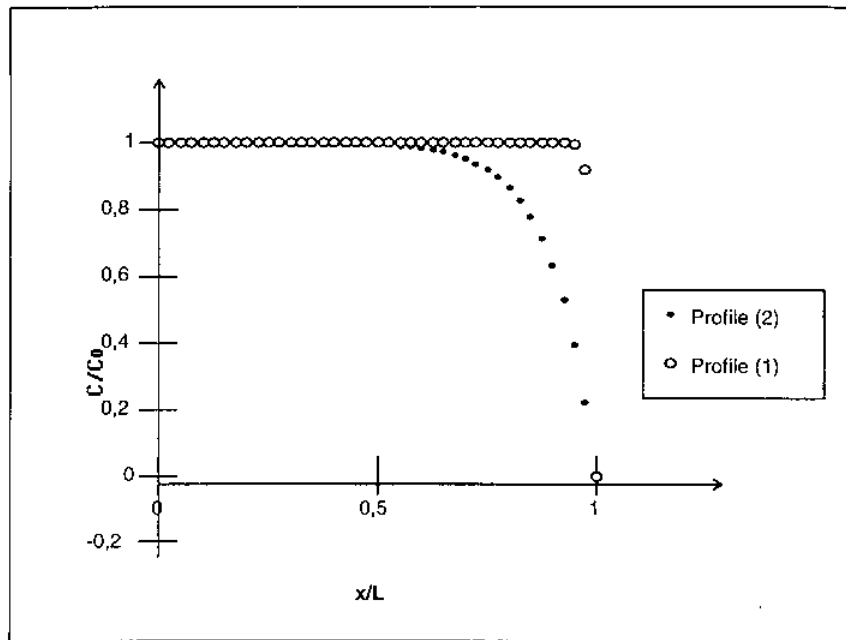


Fig. 4: Profiles of chloride penetration for various potentials

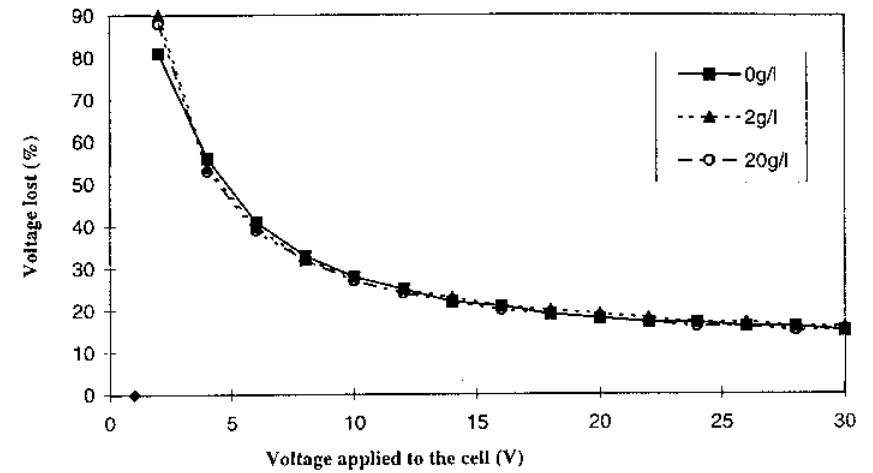


Fig. 5: potential lost in the migration cells.

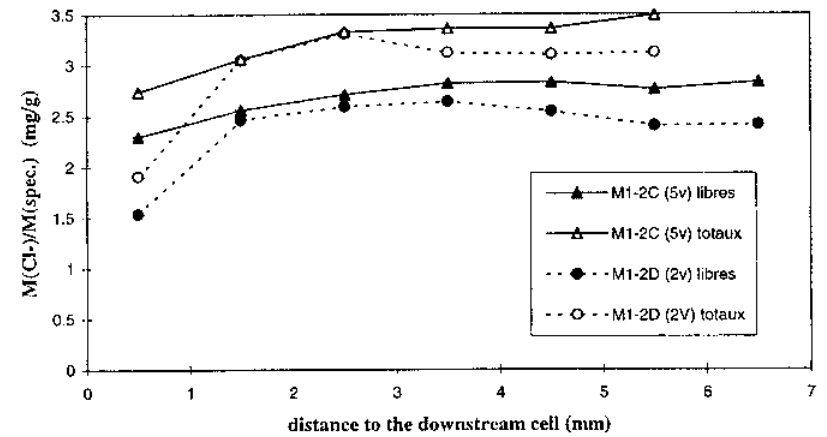


Fig. 6: Free and total chloride concentrations throughout the mortar sample after a migration test.

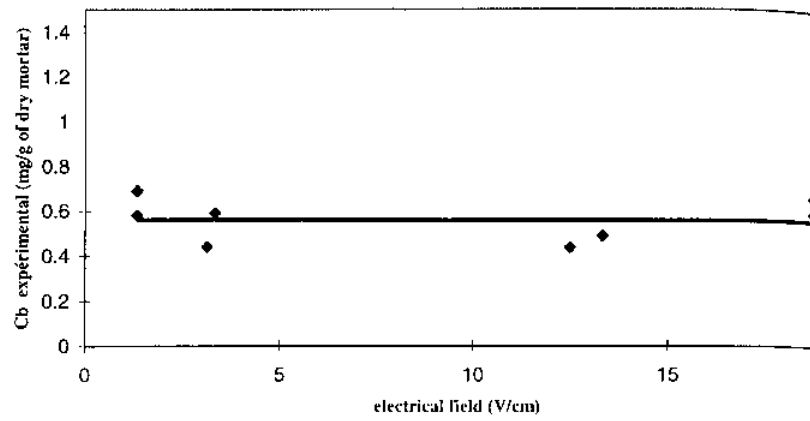


Fig. 7: Influence of electrical field on binding

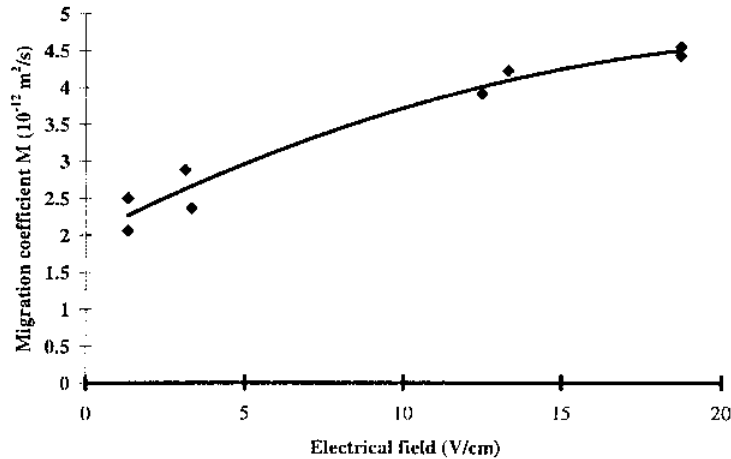


Fig.8: Influence of the electrical field on migration coefficient.

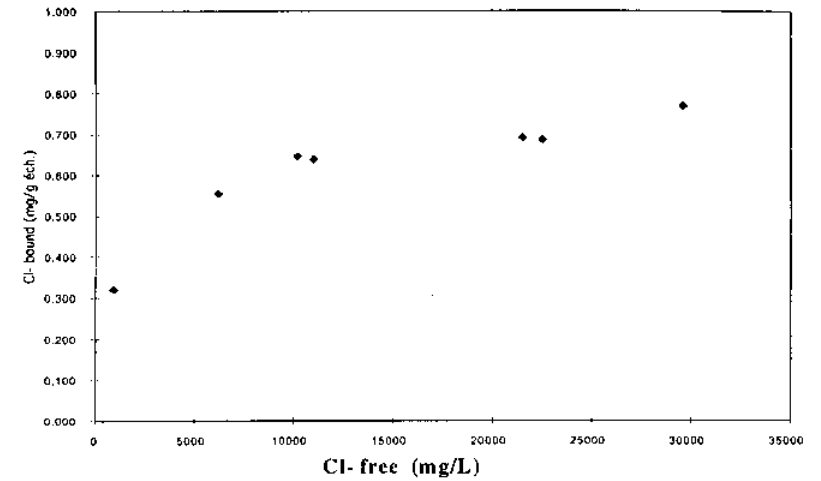


Fig. 9: Binding isotherm from migration tests.

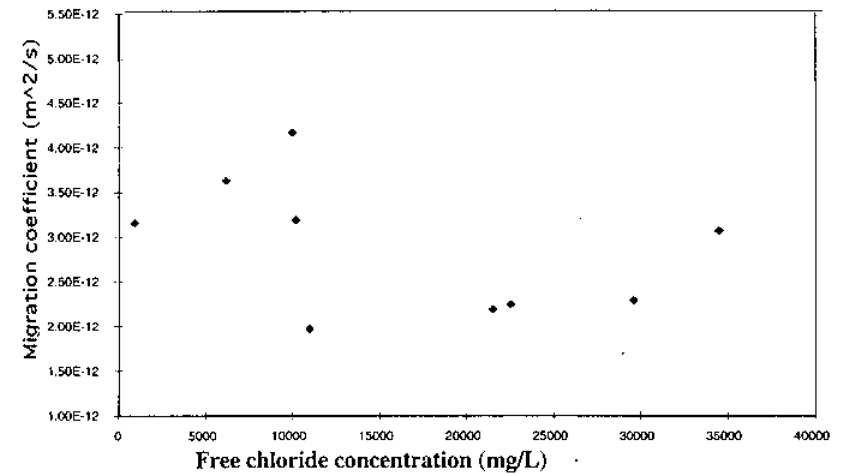


Fig. 10: Influence of the chloride concentration on the migration coefficient.