A CONTRIBUTION TO THE DEVELOPMENT OF PERFORMANCE-RELATED DESIGN METHODS

A. Bettencourt Ribeiro[1], Angela Machado[1], Arlindo Gonçalves[1] and Manuela Salta[1]
[1]National Laboratory of Civil Engineering, Lisbon, Portugal

Abstract: Concerning the durability of concrete, Annex F of European Standard EN 206-1 gives recommendations for limiting values of concrete composition. The in-situ performance and durability related properties measured in laboratory of eight concrete mixtures were evaluated. The composition of these mixtures fulfils the limiting values of different exposure classes related to carbonation-induced corrosion and chloride-induced corrosion, as defined in EN 206-1. Correlations between laboratory properties and in-situ performance are presented. This approach is intended to be used as a basis in defining performance-related design methods with respect to durability.

1. Introduction

The European Standard EN 206-1 (1) establishes the requirements for concrete to withstand environmental actions in terms of limiting values for concrete composition and established concrete properties, and gives guidelines on the use of performance-related design methods, as an alternative approach for concrete durability.

In the first case, the requirements for each exposure class are specified in terms of:
- permitted types and classes of constituent materials;
- maximum W/C;
- minimum cement content;
- minimum concrete compressive strength class (optional);
- minimum air-content of the concrete (if relevant).

Annex F of European Standard gives recommendations for choosing the limiting values, when using cement CEM I conforming to EN 197-1 (2) and aggregates with maximum nominal upper size in the range of 20 mm to 32 mm.

In the second case, the requirements related to exposure classes may be established by using performance-related design methods. Annex J of European Standard provides general guidance on the use of these methods, but without prescribing values for the relevant properties.

An empirical prescriptive method has been used in the last decade. However, considering several advantages of replacing this method by performance-related design methods (3, 4), a previous study was carried out in order to evaluate if some performance tests could be used to distinguish different concrete mixtures, with distinct aggressive environment resistance (5). This study showed that oxygen permeability, capillary absorption, rapid chloride penetration, and accelerated carbonation laboratory test results were well correlated with field behaviour of concrete specimens exposed to aggressive attack by carbon dioxide and chloride ions.

The main objective of this work is to analyse the correlation between laboratory test results and in-situ behaviour. These results are also incorporated in analytical models, in order to identify the relative influences of each performance property.

2. Materials

Eight concrete mixtures were prepared using two types of cement: a portland cement CEM I 32.5 R and a pozzolanic cement CEM IV/B 32.5, in accordance with EN 197-1 (2). Limestone coarse aggregates and natural silica sand were used. Concrete mixtures included three water reducing admixtures: Pozzolith 390 N, based on modified lignosulphonates; Rheobuild 1000, based on polynaphthalene sulphonated condensate; and Glenium 27, based on polycarboxilic acid. Silica fume was also used in some mixtures. Tables 1, 2 and 3 show the properties of the cements and aggregates used.

Table 1: Chemical analysis of cements CEM I 32.5 R and CEM IV/B 32.5

Component	CEM I 32.5 R (%)	CEM IV/B 32.5 (%)
SiO_2	20.0	32.0
Al_2O_3	5.7	13.8
Fe_2O_3	3.0	5.4
CaO	60.8	36.7
MgO	1.6	1.9
K_2O	0.3	1.1
Na_2O	0.2	0.1
C_3S*	45.8	-
C_2S*	22.7	-
C_3A*	10.1	-
C_3AF*	9.2	-
Loss on ignition	3.6	3.2
Insoluble residue	2.2	33.0
Sulfates (SO_3)	2.4	2.0
Chlorides	0.02	0.02

*According to Bogue expressions

Table 2: Composition of cements CEM I 32.5 R and CEM IV/B 32.5

Cement	Clinker (%)	Fillers (%)	Fly ash (%)	Calcium sulphate (%)
CEM I 32.5 R	90.9	5	-	4.1
CEM IV/B 32.5	54.3	3	39.3	3.4

Table 4 presents the proportions of the eight concrete mixtures. This table indicates also the slump value, the W/Cm and the 28-day compressive strength on 150 mm cubic specimens.

Table 3. Properties of aggregates

Aggregate	Bulk specific gravity – SSD (kg/m^3)	Fineness modulus	Maximum size (mm)	Absorption (%)
Coarse aggregate 2	2690	7.23	25.0	0.6
Coarse aggregate 1	2670	6.22	12.5	0.9
Sand	2600	2.63	2.36	0.4

Table 4. Proportions of concrete mixtures

Materials (kg/m^3)	Concrete mixtures							
	A1	**B1**	**C1**	**D1**	**A2**	**B2**	**C2**	**D2**
Coarse aggregate 1	316	329	345	513	336	348	368	548
Coarse aggregate 2	796	865	867	735	799	871	875	745
Sand	788	719	657	389	732	656	587	279
CEM I 32.5 R	260	300	340	530	-	-	-	-
CEM IV/B 32.5 R	-	-	-	-	260	300	340	530
Silica fume	-	-	-	50.7	-	-	-	50.7
Water	169.3	150.7	153.3	177.3	169.3	151.9	153.3	177.3
Admixture 1*	2.51	-	-	-	2.51	-	-	-
Admixture 2*	-	3.60	4.11	-	-	3.60	4.11	-
Admixture 3*	-	-	-	13.3	-	-	-	13.3
Slump (mm)	70	130	180	120	150	180	180	140
W/Cm	0.65	0.50	0.45	0.30	0.65	0.50	0.45	0.30
28-day compress. strength, (MPa)	36.9	49.6	52.9	80.7	32.4	46.4	52.5	76.2

*Admixture 1 based on modified lignosulphonates; Admixture 2 based on polynaphthalene sulphonated condensate; and Admixture 3 based on polycarboxilic acid

Table 5 shows the limiting values for composition and properties of concrete presented in Annex F of EN 206-1 (1), for the exposure classes related to corrosion induced by carbonation and seawater chlorides.

Table 5: Exposure classes according to EN 206-1

	EXPOSURE CLASSES						
	Carbonation-induced corrosion				Chloride-induced corrosion		
	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3
Maximum W/C	0.65	0.60	0.55	0.50	0.50	0.45	0.45
Minimum strength class	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45
Minimum cement content (kg/m^3)	260	280	280	300	300	320	340

The eight mixtures used in this study fulfil the limiting values established in Table 5 for different exposure classes, as presented in Table 6.

Table 6: Exposure classes that limiting values are fulfilled

Concrete mixture	Exposure class
A1	XC1
B1	XC4 and XS1
C1	XS3
D1	>XS3
A2	XC1*
B2	XC4* and XS1*
C2	XS3*
D2	>XS3*

*This assumption is not entirely correct since the recommended limiting values of EN 206 are established for CEM I and not CEM IV/B.

3. Test Methods

3.1 Tests on Laboratory Specimens

For each mixture, a series of tests on laboratory specimens was carried out to determine some concrete properties relevant to the degradation processes of concrete.

The properties determined were: Cembureau oxygen permeability; capillary absorption; non-chloride diffusion coefficient under migration non-steady state; and resistance to accelerated carbonation.

3.1.1 Oxygen Permeability and Capillary Absorption

Oxygen permeability and capillary absorption tests were performed on cylindrical specimens (150 mm diameter and 50 mm height) cut from the inner part of standard cylindrical specimens with 300 mm height. The standard specimens were removed from the moulds at 24 hours and then stored in a moist curing room (20 ± 2ºC and >95% RH). At 7 days, the standard specimens were taken from the moist environment and cut in to three smaller cylinders (50 mm high). These were then placed in a drying oven at 50ºC for 72 hours. Afterwards, the curved edges of the specimens were covered with an adhesive tape. The specimens were then sealed and kept until 27 days in the drying oven, at the same temperature, for humidity redistribution. They were then placed in a laboratory room at 65% RH for 24 hours, in order to reduce their temperature to 20ºC, before the oxygen permeability measurements.

The permeability measurements were conducted in accordance with the Cembureau method (6). The absolute applied pressures were: 0.15, 0.20, 0.25, 0.30, and 0.35 MPa.

After the permeability measurements had been taken, the specimens were placed in a water container for the capillary absorption test, which was carried out following procedure 4.2 of reference (7). However, the water uptake was measured at time intervals of 15 minutes, 30 minutes, 1 h, 2 h, 4 h, 8 h, 24 h, and 48 h.

The mean values and standard deviation of oxygen permeability and capillary absorption coefficients were calculated for each mixture.

3.1.2 Chloride diffusion coefficient in non-steady state conditions by the Migration test using the NT Build 492 standard

Concrete cylinders with 100 mm diameter and 200 mm height have been cast. For each concrete mixture three concrete slices with 50 mm thickness cut from the middle of the concrete cylinders have been tested following NT Build 492 (8) specification, at the temperature of 23 ± 2ºC. Chloride diffusion coefficients have been estimated using the solution of Nernst – Planck equation given by the equation (1).

$$\mathrm{Dns} = \frac{RT}{zFE}\,\frac{x_d - \alpha\sqrt{x_d}}{t} \tag{1}$$

where,

$$\alpha = 2\sqrt{\frac{RTL}{zF\Delta E}} \cdot \mathrm{erf}^{-1}\left(1 - \frac{2Cd}{Co}\right) \tag{2}$$

with z- chloride ion valence , F- Faraday constant, E=(U-2)/L and U – potential applied, L – thickness of concrete specimen, R – real gas constant, T- temperature, x_d – chloride penetration depth, Cd –the chloride content sensible to change the colour , Co – chloride content on the catholyte solution and t – test duration.

3.1.3 Resistance to Accelerated Carbonation

Concrete resistance to accelerated carbonation was measured using a laboratory procedure similar to prEN 104-839 (9). Cubic concrete specimens were stored for 7 days in a moist curing room (20 ± 2ºC and >95% RH), after which, they were preconditioned at 65 ± 5% RH and 23 ± 3ºC, for 14 days. At 28 days, the specimens were then carbonated in a cabinet with controlled humidity, temperature, and carbon dioxide content (65 ± 5% RH, 23 ± 3ºC and 5 ± 0.1% CO_2), for 60 days. Periodically, the carbonation depth was measured applying a phenolphthalein colour indicator on a broken concrete surface. The time evolution of carbonation depth (d_{CO_2}) was adjusted to the relation $d_{CO_2} = k_{carb}\, t^{1/2}$, and the accelerated carbonation coefficients (k_{carb}) were calculated for the different mixtures tested.

3.2 Tests on Field Specimens

For each concrete mixture, 100 × 100 × 510 mm^3 concrete prisms were cast. The specimens were removed from the moulds at 24 hours, and then they were stored for six days in a moist curing room (20 ± 2ºC and >95% RH). The specimens were then kept under standard laboratory conditions of 20 ± 2ºC, 65 ± 5% of RH for 14 days. An epoxy-based coating was applied on the lateral surfaces of the concrete specimens to obtain unidirectional penetration of aggressive agents. Specimens were then exposed to five different field conditions, presented in Table 7.

Table 7: Location of field concrete specimens and exposure classes

Location of concrete specimens	Type of attack	Exposure Class according EN 206-1
Urban sheltered location*	carbonation	XC1
Urban non-sheltered location*	carbonation	XC4
Sea water airborne salt**	chloride penetration and carbonation	XS1 -
Marine tidal zone**	chloride penetration	XS3
Permanently submerged**	chloride penetration	XS2

* Lisbon city; ** Lisbon Atlantic coast

After one year of exposure, two cores from each concrete specimen were taken. From each core, a profile grinding technique was used to obtain powder samples at different depths from the exposed surface. Based on the chloride profiles, the depth where the chloride content reached 0.4% (by weight of binder) was estimated.

Carbonation depth was also measured after one year, using the phenolphthalein method (10).

4. Results and Discussion

Table 8 presents the results of tests performed on laboratory specimens.

Table 8: Tests results of laboratory specimens at 28 days

Concrete mixture	Laboratory tests			
	Oxygen permeability coefficient × 10^{-18} (m^2)$^{(1)}$	Capillary absorption coefficient ($kg/m^2h^{1/2}$)$^{(1)}$	Chloride diffusion coefficient × 10^{-12} (m^2/s)$^{(2)}$	k_{carb} (mm/day ^{½})
A1	84.7 ± 9.7	0.532 ± 0.051	40.9 ± 2.0	2.1
B1	17.5 ± 1.8	0.215 ± 0.021	15.4 ± 1.7	1.2
C1	15.2 ± 3.2	0.245 ± 0.024	21.3 ± 2.0	0.7
D1	5.6 ± 1.3	0.092 ± 0.001	2.7 ± 0.2	0.1
A2	115 ± 20	0.733 ± 0.042	41.6 ± 1.4	4.7
B2	37.2 ± 15	0.254 ± 0.017	11.0 ± 1.2	2.5
C2	27.6 ± 4.9	0.206 ± 0.017	10.8 ± 0.2	1.9
D2	11.2 ± 6.6	0.187 ± 0.030	1.3 ± 0.0	0.5

(1) Mean value and standard deviation of 6 results; (2) Mean value and standard deviation of 3 results

Table 9 exhibits the results of carbonation depth and chloride penetration depth obtained on the specimens after one year of exposition in the field conditions.

Table 9: Field-tests results after 1 year of exposure

Concrete mixture	Carbonation depth (mm)*			Chloride penetration depth (mm)*		
	Airborne salt	Urban sheltered	Urban non-sheltered	Airborne salt	Tidal zone	Permanently submerged
A1	5.0	7.5	5.7	14.0	29.0	34.5
B1	3.0	5.0	3.5	8.5	17.5	24.5
C1	2.9	4.7	3.7	7.5	17.0	24.0
D1	0.6	1.8	1.1	5.0	8.5	9.0
A2	7.0	11.6	9.3	16.5	28.0	29.0
B2	4.5	6.7	5.9	13.5	16.5	16.0
C2	4.1	7.8	5.4	6.5	14.0	14.5
D2	1.2	2.7	2.0	6.0	10.0	10.0

*Mean values

The presented values show that it is possible to classify different concrete mixtures based on the measured performance properties. In fact, different concrete mixtures present distinct properties. Figures 1 to 8 show correlations between performance properties and the concrete's field behaviour.

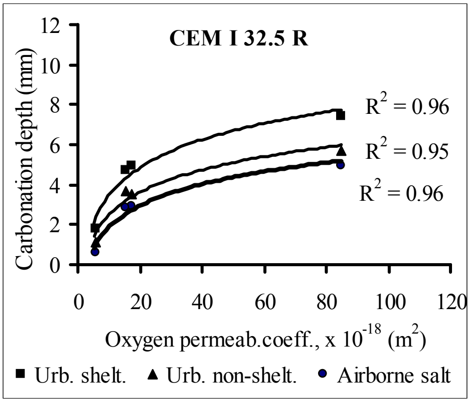

Figure 1: Carbonation depth at 1 year of exposure versus oxygen permeability coefficients for CEM I 32.5 R concrete mixtures

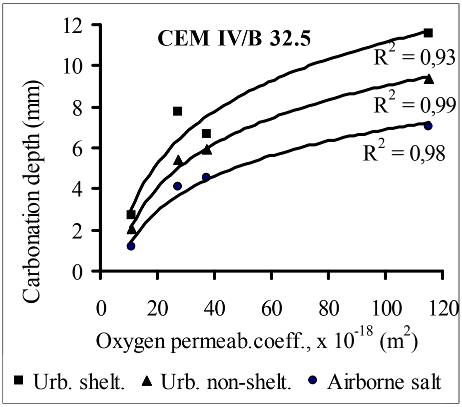

Figure 2: Carbonation depth at 1 year of exposure versus oxygen permeability coefficients for CEM IV/B 32.5 concrete mixtures

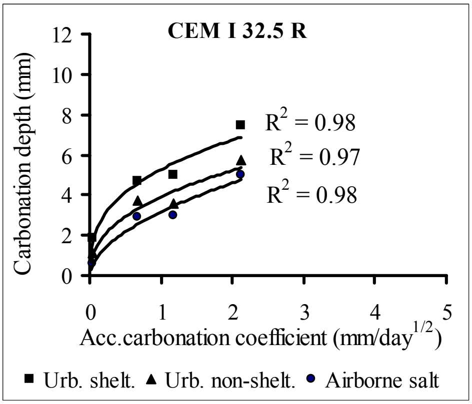

Figure 3: Carbonation depth at 1 year of exposure versus the accelerated carbonation coefficients for CEM I 32.5 R concrete mixtures

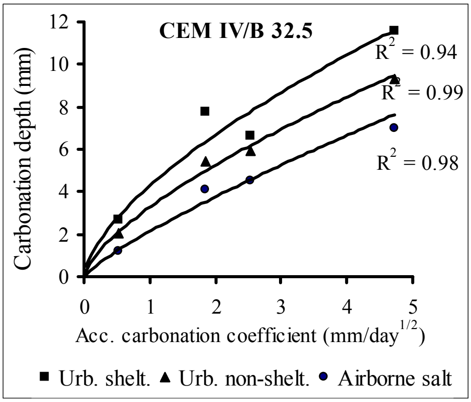

Figure 4: Carbonation depth at 1 year of exposure versus the accelerated carbonation coefficients for CEM IV/B 32.5 concrete mixtures

As expected, the field behaviour of specimens depends not only on the concrete properties but also on the exposure condition and on the cement type used. Figures 1-4 indicate a carbonation increase with:

- increase of environment CO_2 content (marine and urban location);
- humidity decrease in specimens (rain protection);
- increase of the oxygen permeability coefficient;
- increase of the accelerated carbonation coefficient;
- decrease of the clinker content (cement type).

Figures 5-8 indicate a chloride penetration increase with:

- increase of chloride content in the environment (environment aggressiveness);
- increase of the capillary absorption coefficient;
- increase of the chloride diffusion coefficient;
- absence of fly ash, for the specimens in sea water (cement type).

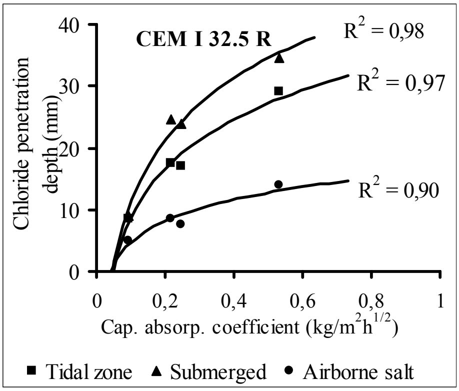

Figure 5: Chloride penetration (0.4%) at 1 year of exposure versus capillary absorption coefficients for CEM I 32.5 R concrete mixtures

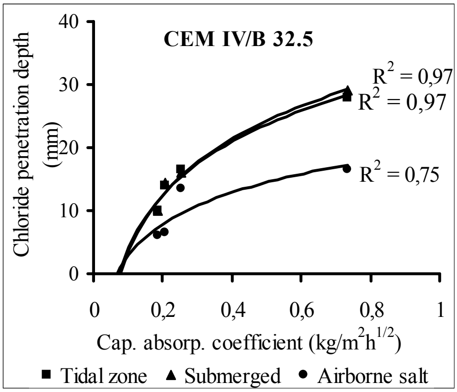

Figure 6: Chloride penetration (0.4%) at 1 year of exposure versus capillary absorption coefficients for CEM IV/B 32.5 concrete mixtures

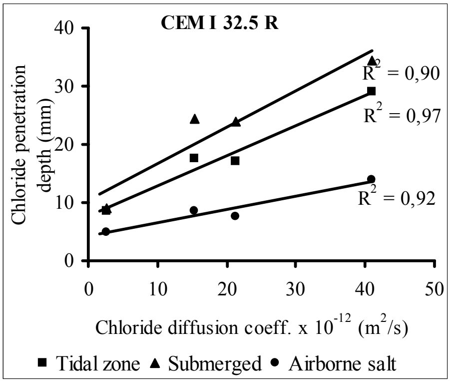

Figure 7: Chloride penetration (0.4%) at 1 year of exposure versus chloride diffusion coefficients for CEM I 32.5 R concrete mixtures

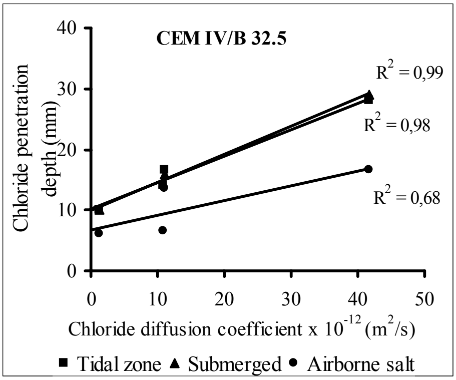

Figure 8: Chloride penetration (0.4%) at 1 year of exposure versus chloride diffusion coefficients for CEM IV/B 32.5 concrete mixtures

The measured performance properties are not capable to evaluate the various parameters that influence the penetration of aggressive agents. However, for the same environment and cement type, it is possible to obtain good correlations between performance properties and field behaviour. The necessity of knowing the type of cement used is a limitative factor for this type of specification approach. The single use of one property seems not be sufficient to develop a performance-related design method. Including additional data can improve the prediction's accuracy. This way, an attempt of using the measured properties, at 28 days, in an analytical model was carried out.

4.1 Prediction of Carbonation Depth

The prediction of carbonation depth, x, using a constant k and the square root of the exposure time, equation (3), is well known and generally gives a good approximation of concrete behaviour.

$$x = k\sqrt{t} \tag{3}$$

The carbonation depth may also be expressed in terms of an oxygen permeability coefficient function, equation (4).

$$x = k\sqrt{t} = f(\text{ox.perm.}, t) \tag{4}$$

Besides the time of exposure, t, the carbonation depth also depends on the $Ca(OH)_2$ present in the concrete interstitial solution. The calcium hydroxide comes from the cement clinker hydration, being a major factor that has to be taken into account.

$$x=f(\text{ox. perm.}, t, \text{binder}) \tag{5}$$

Since the oxygen permeability was measured at 7 days, the function f(binder, t) was determined considering the different hydration of the binders.

With the one year carbonation results it was possible to determine the best fitting function.

$$f(\text{ox. perm.}, \text{binder}, t) = (k_1.\ln(10^{18}\,\text{kox}) + k_2) \times f(\text{binder}, t); \tag{6}$$

$$f(\text{binder}, t) = \begin{cases} \sqrt{\dfrac{t}{365}}, & \text{CEM I} \\ \dfrac{CI}{CIV} \times k_3 \sqrt{\dfrac{t}{365}}, & \text{CEM IV / B} \end{cases} \tag{7}$$

where:
kox. – oxygen permeability coefficient (m^2),
CI – CEM I clinker content (%),
CIV – CEM IV/B clinker content (%),
k_1, k_2 – environment depending constants,
k_3 – concrete age depending constant.

Figure 9 shows a relation between estimated values and one year in-situ results, for urban sheltered specimens, considering $k_1 = 2.41$, $k_2 = -2.44$, and $k_3 = 1.39$.

As can be seen, a good correlation can be obtained between carbonation and oxygen permeability, when considering the type of binder in the analytical model.

Using the accelerated carbonation coefficient, figure 10 the estimation has a similar accuracy. However this test is more time consuming, nearly 3 months, compared with the 28 days needed for the oxygen permeability test.

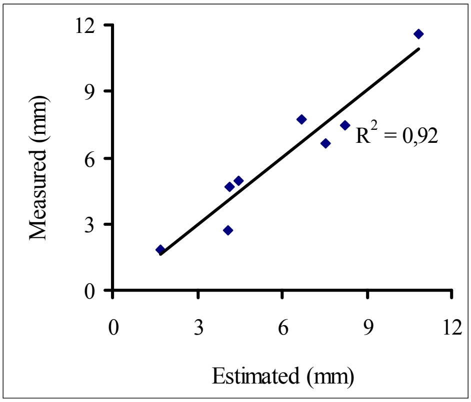

Figure 9: Carbonation penetration depth in-situ measured results versus estimated results for urban sheltered specimens

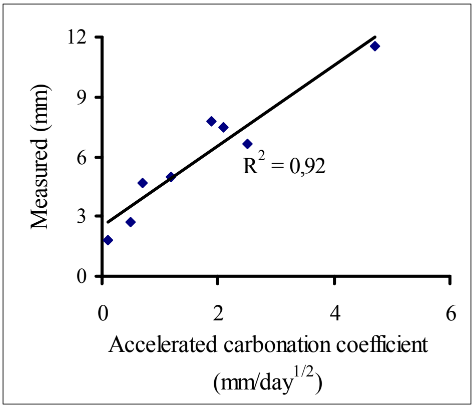

Figure 10: Carbonation penetration depth in-situ measured results versus accelerated carbonation coefficient

4.2 Prediction of Chloride Penetration

Assuming that the 2nd Fick´s Law is applicable, for chloride diffusion, an approximated solution is given by (3)

$$C(x,t) = C_S\left[1 - \frac{x}{2\sqrt{3Dt}}\right]^2 \tag{8}$$

where

$C(x, t)$ – chloride concentration at distance x (kg/m^3),
C_S – chloride concentration at exposed surface (kg/m^3),
x – distance from exposed surface (m),
D – chloride diffusion coefficient (m^2/s),
t – immersion duration (s).

Using this equation it is possible to obtain the distance x_0 where a chloride concentration of 0,4% is reached by diffusion, assuming C_S equal to the environment chloride concentration.
Affecting this value by a certain constant, k_D, in order to consider the aging due to cement hydration and the binding effect, it is possible to estimate the chloride ingress by diffusion.

In the early age, the mass ingress into concrete in contact with a liquid is mainly due to capillary suction. Consequently, this phenomenon has influence on the chloride concentration of concrete, which can be expressed by the capillary absorption coefficient, corrected by an aging factor, k_A.

This way, the chloride ingress can be predicted by the sum of these two processes.

$$x(\text{cap.abs.}, C_S, D, t) = k_A.f(\text{cap. abs.}) + k_D.x_0(C_S, D, t) \tag{9}$$

with k_A, k_D constants, and f(cap. abs.) = A × kcap. f(t), A (m^2) is the contact area, kcap. (kg/m^2.h$^{1/2}$) is the capillary absorption coefficient, and f(t) a time function.

Considering f(t)=1, for one year, the depth (mm) where the chloride concentration reaches 0,4 %, x, is estimated by:

$$x = k_A.A \times kcap + k_D.x_{0(1\ year)}\ (mm) \tag{10}$$

Figure 11 exhibits the chloride penetration estimated values as well as the in-situ results, for the immersed specimens, using $k_A = 1.47$, $k_D = 0.23$ and $C_S = 20.3$ kg/m^3.

The combination of diffusion and capillary absorption gives a better estimation of chloride penetration than the estimation given by the use of individual performance properties, shown in figures 12 and 13.

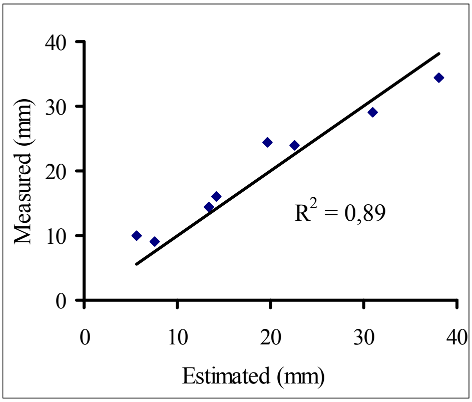

Figure 11: Chloride penetration depth of immersed specimens: in-situ measured values versus estimated results

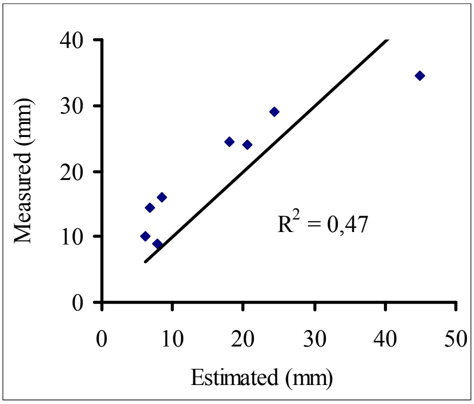

Figure 12: Chloride penetration depth of immersed specimens: in-situ measured values versus estimated results. Only with capillary absorption contribution, $k_D = 0$;

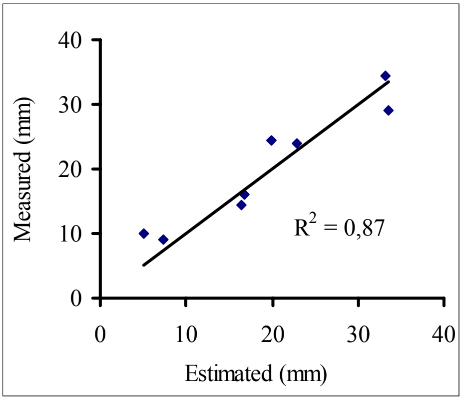

Figure 13: Chloride penetration depth of immersed specimens: in-situ measured values versus estimated results. Only with chloride diffusion contribution, $k_A = 0$

5. Conclusions

Based on the results obtained in this study, the following conclusions can be drawn.

Oxygen permeability, capillary absorption, chloride diffusion by migration, and accelerated carbonation tests can be used in performance-related design methods. The single use of one property seems not be sufficient to develop a performance-related design method. Including additional data from the mixture and a combination of different properties may improve the prediction's accuracy.

The field behaviour of specimens exposed to aggressive attack by carbon dioxide and chloride ions showed good correlation with analytical models based on the results of measured properties.

6. References

1. CEN – European Committee for Standardization, 'EN 206-1, Concrete – Part 1: Specification, performance, production and conformity'; Brussels, Belgium, December 2000.
2. CEN – European Committee for Standardization, 'EN 197-1, Cement Part – 1: Composition, specifications and conformity criteria for common cements'; Brussels, Belgium, April 2001.
3. Gonçalves, A., 'Durability of concrete' (National Laboratory of Civil Engineering, Lisbon, Portugal, April 1999).
4. Rostam, S. and Geiker, M.R., 'Will performance specifications improve the quality of structures?'; Proceedings of the International ECSN Symposium European Concrete Standards in Practice, Copenhagen, Denmark, May 1997, 275-284.
5. Ribeiro, B., Gonçalves, A., Salta, M. and Machado, A., 'Performance of concrete with an intended working life of 50 years'; Paper to be presented at CANMET 2003 Conference.
6. Kolleck, J.J., 'The determination of permeability of concrete by Cembureau method: a recommendation'; *Materials and Structures*, **22** (RILEM, Paris, France, 1989) 225-230.
7. RILEM TC 116-PCD, 'Permeability of concrete as a criterion of its durability'; *Materials and Structures*, **32** (RILEM, Paris, France, April 1999) 174-179.
8. NT Build 492, 'Concrete, Mortar and Cement – Based Repair Materials: Chloride Migration coefficient from non-state migration experiments' (Publisher NORDTEST, Espoo, 1998).
9. CEN – European Committee for Standardization, 'prEN 104-839 – Carbonation resistance'; Brussels, Belgium, February 1997.
10. RILEM Concrete Permanent Committee, 'RILEM Draft Recommendation – Measurement of hardened concrete carbonation depth CPC-18'; *Materials and Structures*, **17** (102) (RILEM, Paris, France, 1984) 435-440.