RESISTANCE OF CONCRETE TO CARBONATION. PREDICTED AND MEASURED VALUES IN NATURAL EXPOSURE

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RESISTANCE OF CONCRETE TO CARBONATION. PREDICTED AND MEASURED VALUES IN NATURAL EXPOSURE

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Abstract

LNEC E 465 specification, in force by the Portuguese National Annex of EN 206-1, makes it possible to estimate the working life of the reinforced concrete structures by the application of models that make use of durability-related performance properties of concrete, such as, resistance to accelerated carbonation and chloride diffusion coefficient.

In a study carried out in LNEC, several concrete mixes were produced with different w/c ratio and cement types, from which concrete specimens were prepared for characterization of relevant properties in laboratory, as well as for exposure in urbane and marine environments.

This article presents and discusses the experimental results of carbonation up to 5 years of natural exposure, these results being compared with values estimated by the methodology established in LNEC E 465.

1. INTRODUCTION

Normally, the definition of the requirements of concrete related with the durability of structures was done by prescription of the composition and by the compressive strength and, only in some cases, limits for some concrete properties were established, such as, water penetration, porosity, chloride diffusion coefficient, carbonation resistance and others.

LNEC E 465 specification [1] develops a semi probabilistic methodology to estimate the performance properties of concrete that make it possible to fulfil the design working life of reinforced and pre-stressed concrete structures design, exposed to carbon dioxide (XC) or chloride (XS) actions.

In a study carried out in LNEC [2] several concrete mixes were produced, which complied with the composition requirements regarding the limits recommended in Annexe F of EN 206-1 [3], for many classes of environmental exposures. Such concrete mixes were characterised in laboratory and specimens were also placed in natural urban and maritime environments. To assess the influence of the cement type on concrete properties other types concrete mixes were also made with identical composition but using CEM IV/B (V) 32,5 R.

Classification in laboratory occurred in accordance with the properties related with the transportation of gases, liquids and ionic species, such as, oxygen permeability, capillary absorption and water absorption, chloride diffusion coefficient by immersion and by migration and carbonation resistance.

This article addresses the carbonation depths obtained up to the moment on concrete specimens exposed to a natural environment, these depths being compared with estimated depths obtained with the methodology included in LNEC E 465 specification [1].

2. CONCRETE FORMULATION

2.1 Materials

The cement was CEM I 32,5 R, CEM I 42,5 R and CEM IV-B(V) 32,5 N, with 39.3% of fly ash. The fine aggregate was a siliceous sand, with a specific gravity of 2590 kg/m^3, fineness modules of 2.63 and a water absorption of 0.4%. In the first stage of the study, calcareous coarse aggregate was used with two maximum sizes, D_{max}, of 25 mm and 12.5 mm, respectively, with a specific gravity of 2690 and 2670 kg/m^3, with fineness modules of 7.23 and 6.22 and water absorptions of 0.6 and 0.9%. In the second stage, granite coarse aggregates were used with two maximum sizes, D_{max}, of 25 mm and 19 mm, respectively, with a specific gravity of 2630 and 2620 kg/m^3, with fineness modules of 7.49 and 6.51 and water absorptions of 0.7 and 0.8%.

2.2 Mixes

Table 1 presents the three types of concrete established in the study [2], showing that the water/cement ratio (W/C) values and the values of cement content (C) are equal to the recommended limits for the environment class exposures presented in Table F.1 of Annex F of EN 206-1 [3]. Concrete designated by letter D represents the formulation of a high performance concrete.

Table 1. Values of W/C and C of the four types of concretes, A, B, C e D

Concrete	Environment classes exposition of Table F.1 of Annex F of EN 206-1	Recommended limits of Table F.1 of EN 206-1	
		W/C $_{max}$	C $_{min}$ (kg/m^3)
A	XC1	0,65	260
B	XC4 or XS1	0,50	300
C	XS3	0,45	340
D*		(0,30)	(530**)

*High performance concrete; ** binder with more 50 kg/m^3 of silica fume (total 580 kg/m^3)

2.3 Conditions of exposure in a natural environment

Concrete specimens were produced with the compositions referred to in Table 2, for laboratory characterization of the relevant properties of concrete and for exposure in natural environments. This article only concerns the specimens in exposure classes, XC3 and XC4, established in EN 206-1 [3] for the carbonation attack.

Table 2. Compositions of four types of concrete, A, B, C and D

Stage of study	Concrete	Type of cement	Cement (kg/m^3)	Silica fume S (kg/m^3)	W/(C+S)	Admixture* (commercial design.)	Slump (cm)
1**	A1	I 32,5 R	260	-	0,65	Pozzolith 390N	15±1
	B1		300	-	0,50	Rheobuild 1000	
	C1		340	-	0,45	Rheobuild 1000	
	D1		530	50	0,30	Glenium 27	
	A2	IV 32,5 N	260	-	0,65	Pozzolith 390N	15±1
	B2		300	-	0,50	Rheobuild 1000	
	C2		340	-	0,45	Rheobuild 1000	
	D2		530	50	0,30	Glenium 27	
2***	A1-L	I 42,5 R	260	-	0,65	none	15±1
	C1-L		340	-	0,45	Rheobuild 1000	15±1
	Z1-L		400	-	0,45	Pozzolith 390N	3±1

* Admixture dosage was established to obtain a fixed value of slump; ** Concrete composition with calcareous coarse aggregate; *** Concrete composition with granite coarse aggregate

Table 3. Exposure environments and exposure classes where concrete specimens were placed

Exposure environment of concrete specimens	Exposure classes according to EN 206-1[3]	
Urban sheltered environment (partially) (Fig. 1)	XC3	LNEC, Lisbon
Urban unsheltered environment (Fig. 2)	$XC4_{urban}$	
Maritime unsheltered environment (Fig. 3)	$XC4_{maritime}$	Raso Sea Cable - Cascais

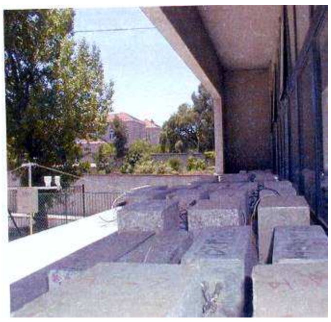
Figure 1. Urban sheltered


Figure 2. Urban unsheltered


Figure 3.Maritime unsheltered

2.4 Tests

This article only presents the test results regarding compressive strength and carbonation depth although the study [2] also assessed several properties related with the transportation of aggressive agents, such as, permeability, capillary absorption, chloride penetration resistance.

Carbonation resistance R_{c65} was determined according to LNEC E 391 specification [5].

After demoulding, specimens were cured in water during 14 days and afterwards in air at 65±2% of relative humidity (RH) and 23±1ºC of temperature until reaching 28 days; and then in a CO_2 camera with 65±2% of RH and 23±1ºC of temperature and 5±1% of CO_2. The side faces of specimens were sealed to force the CO_2 ingress to occur only through extremities.

Carbonation depth was determined according to the methodology described in LNEC E 391 specification [5], on simple concrete specimens placed in natural, maritime and urban environments. Side faces of specimens were sealed with epoxy resin, in order to achieve a unidirectional CO_2 penetration. In the first stage, specimens were used with a cross-section of 10 cm x 10 cm and a length of 51 cm, and in the second stage, the specimens used had a cross-section of 15 cm x 15 cm and a length of 30 cm.

3. ESTIMATION OF CARBONATION DEPTH

The carbonation resistance, Rc65, of the eleven types of concrete referred to in section 2.2 was experimentally obtained through the eq.7 included in section 6.2.1 of LNEC E465 [1].

$$R_{c65} = \frac{2.c_{accel}}{k_{accel}} \qquad (1)$$

c_{accel} (kg/m^3) being the CO_2 concentration in accelerated testing, k_{accel} (mm/t^{½}) being obtained from eq.2 in which X(m) is the carbonation depth, and t(years) the exposure time of concrete.

$$X = k_{accel}.\sqrt{t} \qquad (2)$$

The eleven experimental values of the R_{c65}, of that concrete were combined in a wide range of results comprising several cements and were analysed in the study published by Gonçalves at al. [6]. According to that study, the R_{c65}, can be estimated by eq.3 and 4:

$$R_{c65} = 0{,}0016.\sigma^{3{,}106} \quad \text{CEM I; II/A} \qquad (3)$$

$$R_{c65} = 0{,}0018.\sigma^{2{,}8618} \quad \text{CEM II/B; CEM III; CEM IV; CEM V} \qquad (4)$$

in which σ (MPa) is the compressive strength of concrete at 28 days.

From the values of R_{c65}, obtained via eqs 3 and 4, an estimation of the carbonation depth of the four types of concretes referred to in section 2.2 was achieved using the model of depth carbonation prediction, X(m), obtained from eq.1 included in section 6.2.1 of LNEC E465[1].

$$X = 0{,}064807.\sqrt{\frac{k_1.t}{R_{c65}}}.\left(\frac{1}{t}\right)^n \qquad (5)$$

in which t(yr) is the exposure time of concrete, k_1 and n the values of the parameters indicated in Table 6 of LNEC E 465[1], for XC3 and XC4, related with humidity and watering periods.

4. RESULTS AND DISCUSSION

Table 4 presents the results obtained in the study [2], referred to above, as regards the compressive strength at 28 days, σ, and the R_{c65} estimated at the time. As expected, it was observed that the carbonation resistance increases with the increase in concrete strength.

With CEM I, the value of R_{c65}, was nearly the double of the value obtained with CEM IV. Table 4 shows the best performance of cement rich in Portland clinker to carbonation attach.

Values of carbonation depth obtained after a 5.3 year exposure in natural environments (which are designated as “real” values), showed a greater progression of carbonation in sheltered environments (urban) for the four types of concrete, as expected (Table 5).

Table 4: Compressive and carbonation strengths for concrete types A, B, C and D

Concrete	Cement type	Compressive strength at 28 days, σ (MPa)	Carbonation resistance, R_{c65} (kg.yr/m^5) Correlations of R_{c65} and σ
A1		36,9	118
B1	I 32,5 R	49,7	297
C1		52,9	361
D1		80,7	1339
A2		32,4	38
B2	IV 32,5 N	46,4	106
C2		52,5	151
D2		76,2	438
A1-L		35,4	104
C1-L	I 42,5R	58,9	504
Z1-L		63,9	649

According to Table 2 included in LNEC E 464 specification [7], the exposure class XC3 includes a moderately wet environment, which can occur on external surfaces of reinforced concrete sheltered from rain transported by wind. As Figure 1 illustrates, specimens placed in a sheltered urban environment, although having been kept under a roof covering, were subject to the influence of rain transported by wind, the specimens near the border being more frequently damped. That situation occurs between XC3 and XC4 exposure classes, but, in this study it is ascribed to XC3.

Figures 4 and 5 show, respectively, the difference in carbonation depths along the 5.3 years, between the two urban environments, both sheltered (XC3) and unsheltered (XC4), and between the two unsheltered environments, both maritime ($XC4_{maritime}$) and urban ($XC4_{urban}$). Figure 6 indicates the air humidity, as well as the watering and drying periods, along the 5.3 year exposure to urban and maritime environments [8].

The difference in carbonation depth between the two urban environments (XC3, XC4 Figure 4) was greater than the difference observed in the two unsheltered environments ($XC4_{maritime}$, $XC4_{urban}$ Figure 5), due to the absence of watering periods in sheltered environments, with the exceptions of 2001 and the period between 2004 and 2006. These exceptions were a result of the facts as follows: i) 2001, in $XC4_{maritime}$ (Figure 6b) there were various watering periods witch delayed the carbonation; ii) between 2004 and 2006, in $XC4_{urban}$ (Figure 6a), the watering periods were short allowing a progression in carbonation, although the drying of specimens occurred more slowly than their watering.

Figures 7 and 8 show the curves of both real and estimated values of carbonation depth along the 5.3 year exposure to the XC3 environment for concretes with CEM I 32,5 R and CEM IV 32,5 N, respectively. Both estimated and real values are practically coincident, showing the different behaviours of CEM I and CEM IV: the concrete with CEM I shows a carbonation depth below 12 mm and the concrete with CEM IV shows a carbonation depth below 21 mm (mainly depending on the W/C ratio and cement dosage).

Figures 9, 10 and 11 show the curves of both real and estimated carbonation depth values along the 5.3 year exposure to the unsheltered environment XC4, both maritime and urban, for the concrete with CEM I 32,5 R, CEM I 42,5 R and CEM IV 32,5 N, respectively. These figures show that, in the first place, the unsheltered environment XC4, both maritime and urban, has led to similar real carbonation depths, with the maritime environment values being lower than the urban environment ones.

Except for the case of concrete with CEM IV 32,5 N, which presented more distant values by the end of the 5.3 years, thus serving to clarify the difference found in Figure 5.

Table 5: Real carbonation depth after a 5.3-year exposure to a natural environment

Concrete	Cement	Carbonation depth (mm)		
		Urban unsheltered $XC4_{urb}$	Mar. unsheltered $XC4_{mar}$	Urban sheltered XC3
A1		8,5	7,8	12,2
B1	I 32,5	4,8	3,8	8,9
C1	R	5,0	3,3	7,1
D1		1,5	1,0	2,5
A2		17,0	11,0	21,5
B2	IV 32,5	10,0	5,3	14,1
C2	N	8,2	4,8	11,8
D2		2,9	1,5	5,7
A1-L		9,3	7,6	-
C1-L	I 42,5R	1,0	0,8	-
Z1-C		0,9	0,6	-

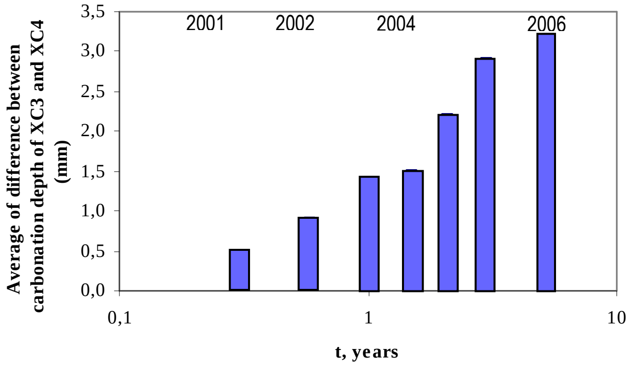

Figure 4. Difference in the carbonation depth along the 5.3-year natural exposure between the two urban environments, both XC3 and XC4

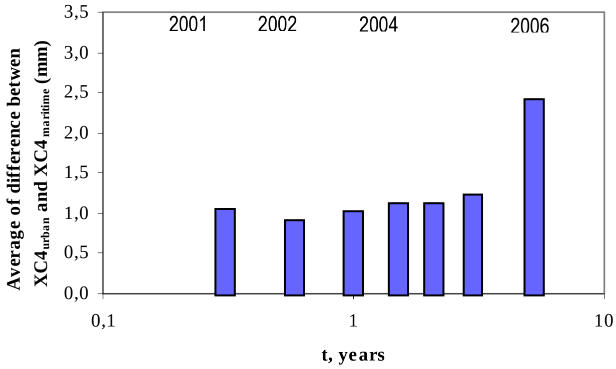

Figure 5. Difference in the carbonation depth along the 5.3-year natural exposure between the two unsheltered environments, both $XC4_{urban}$ and $XC4_{maritime}$

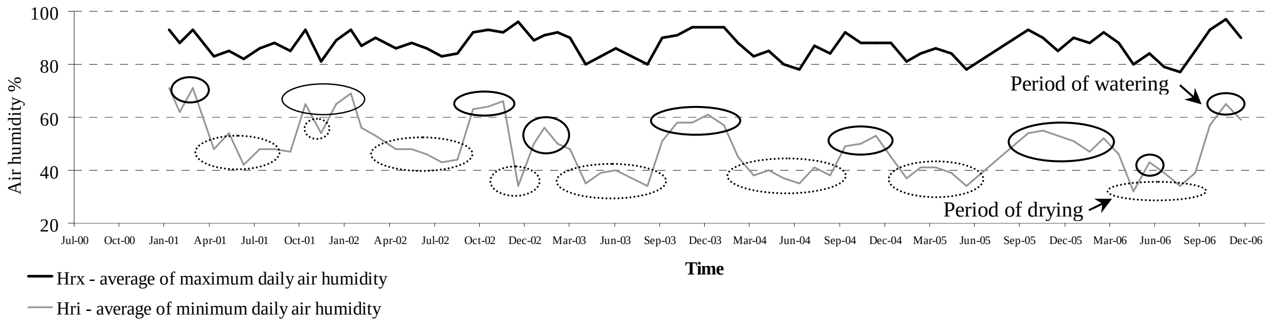

Figure 6 a): Average of max and min daily air humidity in urban environment

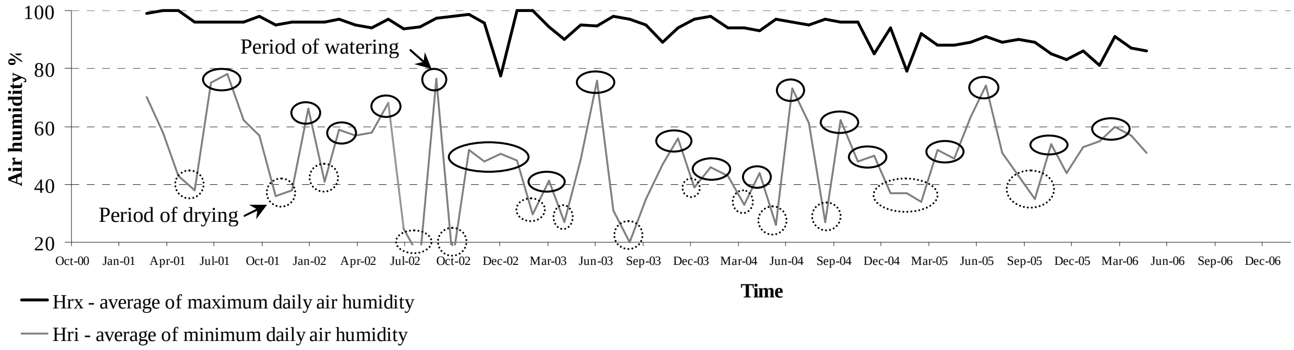

Figure 6 b): Average of max and min daily air humidity in exposure maritime environment

In the second place, estimated values were very close to real values, except in the case of concrete C1-L and Z1-L, Figure 10. Also, concrete C1-L exhibited less carbonation depth than concrete C1 (Figure 9 Table 5) as a consequence of it being more resistant (58.9 MPa, Table 4) than concrete C1 (52.9 MPa, Table 4), or due to the high fineness of CEM I 42.5 R.

Consequently, we can assume that, although carbonation resistance, R_{c65}, was obtained from compressive strength at 28 days, it made possible to achieve carbonation depth values close to real values, by making use of the model indicated in LNEC E 465 [1]. The average difference between real and estimated values was close to 1mm, at the end of the 5.3 years.

5. FINAL REMARKS

The final conclusion on the reliability of the model indicated in LNEC E 465 [1], as refers to the carbonation depth achieved by concrete exposure to XC environments, only is possible after several exposure years and after using many test specimens.

However, the results obtained, at this moment, suggested that the model is fairly adequate for performing carbonation depth measurements. Therefore, it seems that LNEC specification [1] overestimates the carbonation depth of concrete with cement CEM I 42,5 R (Figure 10) and of concrete placed under maritime exposure. The inverse is observed on concrete with cement CEM IV and exposed to urban environments.

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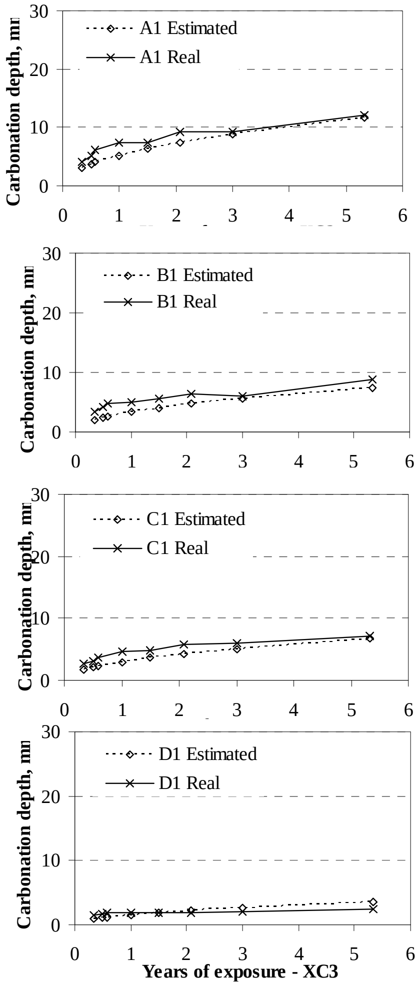

Fig. 7. Carbonation depth for concretes with CEM I 32,5R, in XC3

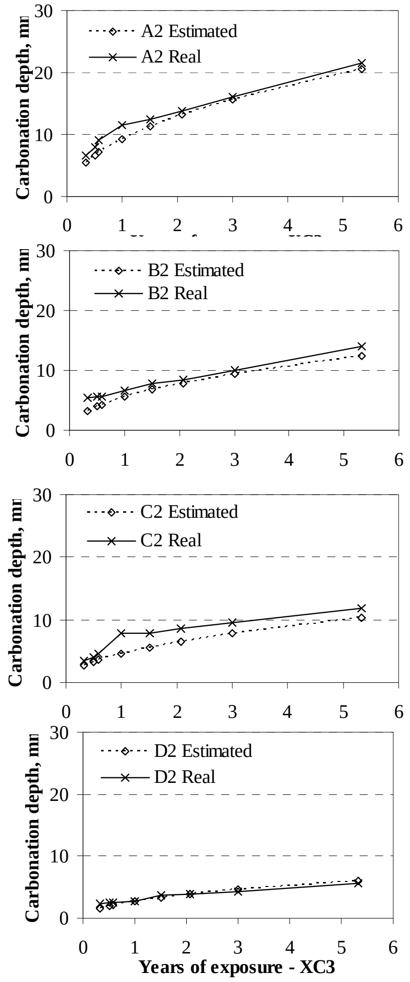

Fig. 8. Carbonation depth for concretes with CEM IV 32,5N, in XC3

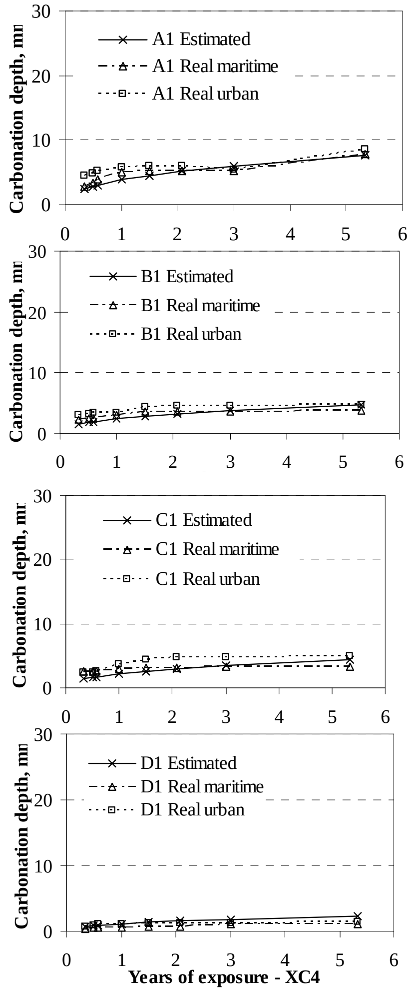

Fig. 9. Carbonation depth for concretes with CEM I 32,5R, XC4

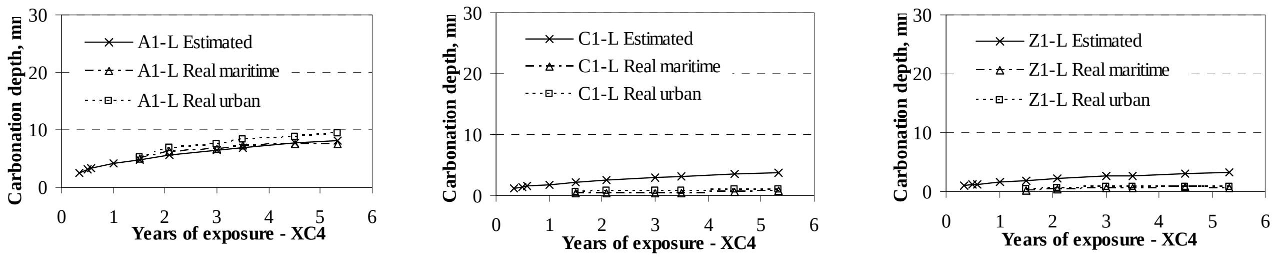

Fig. 10. Carbonation depth for concretes with CEM I 42,5 R, in unsheltered environmental XC4

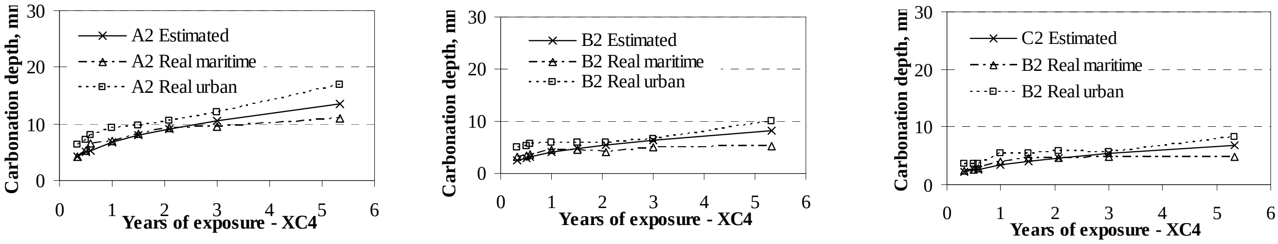

Fig. 11. Carbonation depth for concretes with CEM IV 32,5 N, in unsheltered environment XC4