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Werkstoffwissenschaften und Bausanierung

Materials Science and Restoration

**Berichtsband des internationalen Kolloquiums
Proceedings of the International Conference**

**Herausgeber/Editor
F. H. Wittmann**

**Veranstalter:
Technische Akademie Esslingen**

**in Zusammenarbeit mit dem Wissenschaftlich-Technischen
Arbeitskreis für Denkmalpflege und Bauwerksanierung e.V. (WTA)**

**6. – 8. September 1983
September 6 – 8, 1983**

**edition
lack
+ chemie**

A model to predict service life of concrete structures

Ein Modell zur Vorhersage der Nutzungsdauer von Betonkonstruktionen

Yves F. HOUST, Pieter E. ROELFSTRA und Prof. Dr. Folker H. WITTMANN
Ecole Polytechnique Fédérale de Lausanne,
Laboratoire des Matériaux de Construction, Lausanne, Schweiz

SUMMARY

The drying process and the migration of carbon dioxide into the porous structure of concrete is described first of all by means of differential equations. It is shown that these two processes are not independent from one another but they are interrelated. On this basis a numerical model is developed to calculate the depth of carbonation as function of time. Several material parameters are included in the analytical description. By means of these parameters it is possible to take concrete composition and degree of hydration into consideration.

As an example it is shown in which way the most essential material parameters of the analytical model can be determined experimentally. Results of a numerical evaluation of the set of equations are discussed and compared with data taken from the literature. If the concrete composition is known the service life of a concrete structure exposed to arbitrary climatic conditions can be predicted.

ZUSAMMENFASSUNG

Zunächst wird das Trocknen und die Diffusion des Kohlendioxides in das poröse Gefüge des Betons mit Hilfe von Differentialgleichungen beschrieben. Es zeigt sich dabei, dass die beiden Vorgänge nicht unabhängig von einander ablaufen, sondern interreliert sind. Darauf aufbauend wird ein analytisches Modell zur Berechnung der Karbonatisierungstiefe als Funktion der Zeit entwickelt. In dem Modell tauchen mehrere Materialparameter auf, mit denen im wesentlichen die Betonzusammensetzung und der Hydratationsgrad berücksichtigt werden.

Beispielhaft wird gezeigt wie wesentliche Einflussgrößen des analytischen Modells experimentell bestimmt werden können. Die Ergebnisse der numerischen Auswertung des Modells werden diskutiert und mit Angaben aus der Literatur verglichen. Wenn die Betonzusammensetzung bekannt ist, kann die Lebensdauer einer Betonkonstruktion unter beliebigen klimatischen Bedingungen vorhergesagt werden.

1. INTRODUCTION

Some twenty years ago few people were really interested in durability of concrete structures. The service life of a given structure was not expected to be limited by deterioration of building materials. Thorough inspection of bridges and other structures which had to be pulled down and replaced to meet their growing task made it quite clear that due to corrosion the lifetime of a structure can be considerably shorter than previously anticipated.

In addition concrete structures have become more and more slender and modern structures have been exposed to extreme environmental conditions such as offshore and heavily industrialized areas. Therefore durability of plain and reinforced concrete under normal and extreme climatic conditions has become a major subject of concern and subsequently of widely spread research activities.

So far many publications, reports and conference proceedings have been published (see for example Ref. /1-5/). It has been pointed out that the rate of

carbonation of the concrete cover above the steel reinforcement is one of the decisive factors in all durability studies. The bulk material of experimental data available cannot be understood and interpreted fully because so far there is no comprehensive theoretical concept of the different mechanisms involved in carbonation and corrosion of reinforced concrete.

Numerical simulation methods allow us today to treat complex interactive processes in a quantitative way. In a first attempt Bazant (Ref. /6/) developed a numerical model to describe the lifetime of reinforced concrete in marine environment.

In this contribution carbonation of concrete is studied by means of a numerical model. All parameters used can be linked with concrete technological data and therefore are fixed for a given mix proportion and an assumed environment. As an example it is shown in which way some of these parameters can be determined experimentally. The final aim of this project is to quantify durability of concrete. This will enable a structural engineer not only to specify mechanical properties of the materials for a concrete structure but also to

demand a degree of durability for any climatic condition.

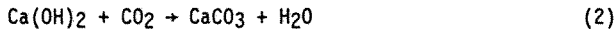
2. THE NUMERICAL MODEL

Young concrete is usually a water saturated porous material. Immediately after demoulding drying starts. It has been shown earlier (Ref. /7/) that drying of concrete can be realistically described by means of a diffusion equation :

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial X} D_W \frac{\partial W}{\partial X} \quad (1)$$

In this equation W stands for the evaporable water content and D_W is the coefficient of moisture diffusion. It has to be noted that D_W strongly depends on moisture content.

If the drying concrete surface is exposed to normal air carbonation will take place at the same time that means that the calcium hydroxide will react with carbon dioxide of the air :



According to equation (2) during this process water is liberated in a concrete specimen. To take this moisture gain into consideration we have to modify equ. (1) :

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial X} D_W \frac{\partial W}{\partial X} + \alpha_1 \frac{\partial C}{\partial t} \quad (3)$$

C stands for the amount of carbonate formed and α_1 is a material parameter which takes cement content and water/cement ratio into consideration. In the next step we have to consider the penetration of carbon dioxide into the porous system of concrete. As a first approximation we can use again the general diffusion equation for the gas diffusion :

$$\frac{\partial G}{\partial t} = \frac{\partial}{\partial X} D_G \frac{\partial G}{\partial X} \quad (4)$$

D_G stands in equation (4) for the coefficient of diffusion of the gas, in our case this is carbon dioxide. D_G depends on the moisture content. During carbonation carbon dioxide gas is consumed. If this loss is taken into consideration the differential equation (4) has to be rewritten in the following form :

$$\frac{\partial G}{\partial t} = \frac{\partial}{\partial X} D_G \frac{\partial G}{\partial X} - \alpha_2 \frac{\partial C}{\partial t} \quad (5)$$

In this equation α_2 is again a material parameter which depends essentially on the concrete composition.

The rate of formation of carbonate in the concrete is given by $\partial C/\partial t$. It is well known that the rate of formation of carbonate depends on the degree of carbonation :

$$f_1(C) = \frac{C_{\max} - C}{C_{\max}} \quad (6)$$

and on the gas concentration :

$$f_2(G) = \frac{P(\text{CO}_2)}{P_s(\text{CO}_2)} \quad (7)$$

Finally the moisture content W has a significant influence on $\partial C/\partial t$:

$$f_3(W)$$

Now we assume that these three major influences on the rate of carbonation can be combined as factors :

$$\frac{\partial C}{\partial t} = \alpha_3 f_1(C) \cdot f_2(G) \cdot f_3(W) \quad (8)$$

where α_3 is again a material constant which takes mix proportions and degree of hydration of a given concrete into consideration.

By using equations (3), (5) and (8) we can study the mutual interaction of drying and diffusion of carbon dioxide on carbonation. A numerical model based on these three equations has been developed. We used the method of finite differences to solve the equations of the numerical model.

3. EXPERIMENTS

3.1. Preparation of five different mortars

As to study some essential influencing factors on carbonation five different types of mortar have been prepared. The composition i.e. the cement/sand ratio and the water/cement ratio are indicated in Table I. In Tab. I the compressive and the tensile strength as measured on prisms (40x40x160 mm) are also given. All specimens have been stored for two months under water before the different tests were carried out.

TABLE I

Composition, compressive and tensile strength of the 5 different mortars determined on prisms 40x40x160 mm at the age of 28 days.

Mortar type	Cement/Sand	Water/Cement	Compressive strength (N/mm ²)	Tensile strength (N/mm ²)
A	1:3	0.45	44.1	8.4
B	1:3	0.50	35.5	7.4
C	1:3	0.55	35.7	8.2
D	1:4	0.55	26.8	5.2
E	1:5	0.60	21.0	5.1

3.2. Water vapor permeability and diffusion coefficient

With a first test series water vapor permeability and the corresponding diffusion coefficient of the five different types of mortar should be determined. Circular discs with a diameter of 100 mm have been sawn to obtain a thickness of 10 mm and then ground to the final thickness of 5 mm. Half of the discs have been carbonated in 100 % CO₂ and at 76 % RH. The remaining half has been stored as to prevent access of CO₂. Then the discs were mounted on cups and the permeability was measured in a first step between 100 % RH at the inside and 76 % RH in the surrounding atmosphere. After a steady state of moisture transfer had been reached the humidity inside the cup has been lowered to 76 % RH and the one of the surrounding atmosphere to 55 % RH. All experiments were carried out at a temperature of 20°C.

The water vapor permeability λ was determined from the measured weight loss by using the well-known formula :

$$J = - \lambda \text{ grad } P \quad (9)$$

In this equation J stands for the flux of moisture and P for the water vapor pressure.

In Table II the experimentally determined values for the water vapor permeability λ are given for all five different types of mortar both in the carbonated and in the not carbonated state.

TABLE II

Water vapor permeability λ in s.

Mortar type	100-76 % RH		76-55 % RH	
	not carbonated	carbonated	not carbonated	carbonated
A	$3.00 \cdot 10^{-12}$	$4.22 \cdot 10^{-12}$	$1.05 \cdot 10^{-12}$	$1.16 \cdot 10^{-12}$
B	$2.18 \cdot 10^{-12}$	$5.45 \cdot 10^{-12}$	$0.92 \cdot 10^{-12}$	$1.41 \cdot 10^{-12}$
C	$3.02 \cdot 10^{-12}$	$6.40 \cdot 10^{-12}$	$1.26 \cdot 10^{-12}$	$1.39 \cdot 10^{-12}$
D	$3.09 \cdot 10^{-12}$	$6.70 \cdot 10^{-12}$	$1.25 \cdot 10^{-12}$	$2.36 \cdot 10^{-12}$
E	$4.29 \cdot 10^{-12}$	$8.40 \cdot 10^{-12}$	$1.89 \cdot 10^{-12}$	$4.60 \cdot 10^{-12}$

The coefficient of diffusion can be obtained from λ by using the following equation (see Ref. /7/):

$$D = \lambda \frac{dP}{dW} \quad (10)$$

The value dP/dW can be derived from the desorption isotherm. For this reason desorption isotherms have been measured and they are reproduced in Fig. 1. The values for the coefficient of diffusion D obtained in applying equation (10) are compiled in Table III.

TABLE III

Coefficient of diffusion D in m^2/s .

Mortar type	100-76 % RH		76-55 % RH	
	not carbonated	carbonated	not carbonated	carbonated
A	$2.74 \cdot 10^{-11}$	$3.85 \cdot 10^{-11}$	$1.57 \cdot 10^{-11}$	$1.73 \cdot 10^{-11}$
B	$1.94 \cdot 10^{-11}$	$4.84 \cdot 10^{-11}$	$1.02 \cdot 10^{-11}$	$1.57 \cdot 10^{-11}$
C	$2.09 \cdot 10^{-11}$	$3.73 \cdot 10^{-11}$	$1.46 \cdot 10^{-11}$	$1.61 \cdot 10^{-11}$
D	$2.81 \cdot 10^{-11}$	$6.13 \cdot 10^{-11}$	$1.89 \cdot 10^{-11}$	$3.58 \cdot 10^{-11}$
E	$3.27 \cdot 10^{-11}$	$6.40 \cdot 10^{-11}$	$3.50 \cdot 10^{-11}$	$8.50 \cdot 10^{-11}$

3.3. Rate of carbonation at different RH

Discs of a thickness of about 5 mm have been cut from prisms (40x40x160 mm). For all five different types of mortar these discs have been equilibrated with different RH in evacuated desiccators. By means of saturated salt solutions the following humidities have been kept constant: 33 %, 55 %, 76 % and 93 %. In addition in one desiccator a RH close to zero has been created by P_2O_5 .

After the equilibrium with the chosen RH had been reached the desiccators have been filled with an atmosphere of 100 % CO_2 . After a duration of 14 days

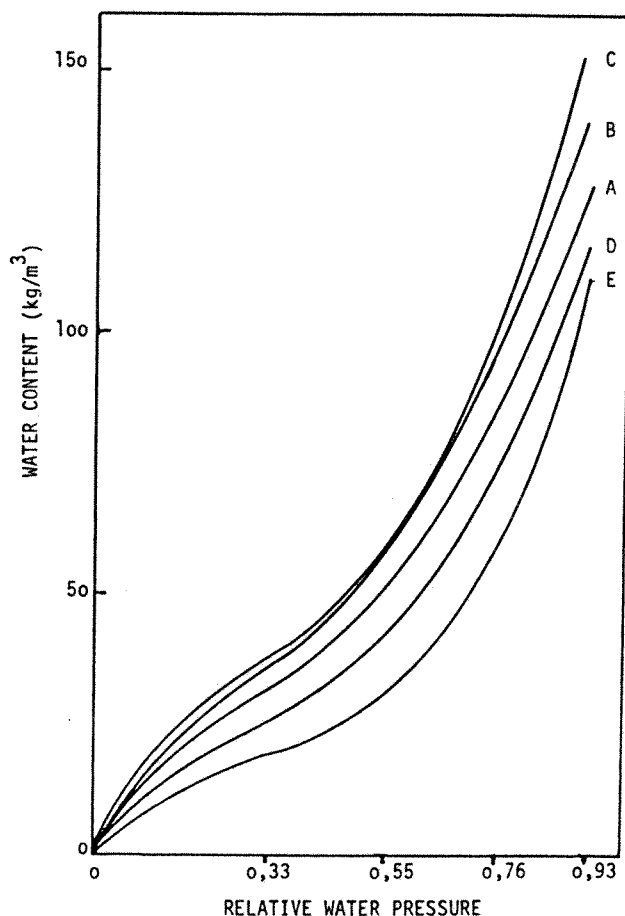


Fig. 1 : Desorption isotherms (200C) for the five different types of mortar.

the degree of carbonation has been determined. All samples have been dried at 105°C and then finally ground. At a temperature of 1200°C the CO_2 has been liberated according to the following equation:



The liberated CO_2 is absorbed in saturated solution of $Ba(OH)_2$ and finally the amount absorbed is determined by coulometric titration.

The amount of CO_2 which has been fixed after 14 days of exposure of the mortar specimens to an atmosphere of 100 % CO_2 at 20°C as function of the RH in which the specimens had been equilibrated before they were brought in contact with 100 % CO_2 is shown in Fig. 2.

3.4. Pore size distribution

Based on earlier findings and in agreement with the measured values of water vapor permeability it is obvious that carbonation changes the microstructure of the material. With the aim to study this influence quantitatively pore size distributions of not carbonated and of carbonated specimens have been measured. A conventional mercury pressure porosimeter which allows the application of pressures of up to 415 N/mm² has been used. This corresponds to a minimum pore diameter of 3,3 nm.

Typical results are shown in Fig. 3. From these results it is evident that pores with a diameter between 10 and 100 nm are largely reduced by carbonation whereas pores bigger than 200 nm are hardly affected. The total porosity after carbonation is decreased.

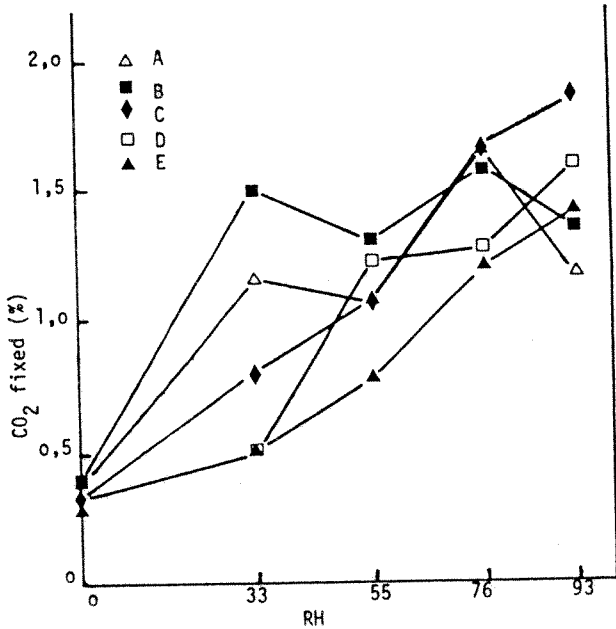


Fig. 2 : Amount of CO₂ (% by mass) fixed after 14 days of exposure to an atmosphere of 100 % CO₂ as function of RH.

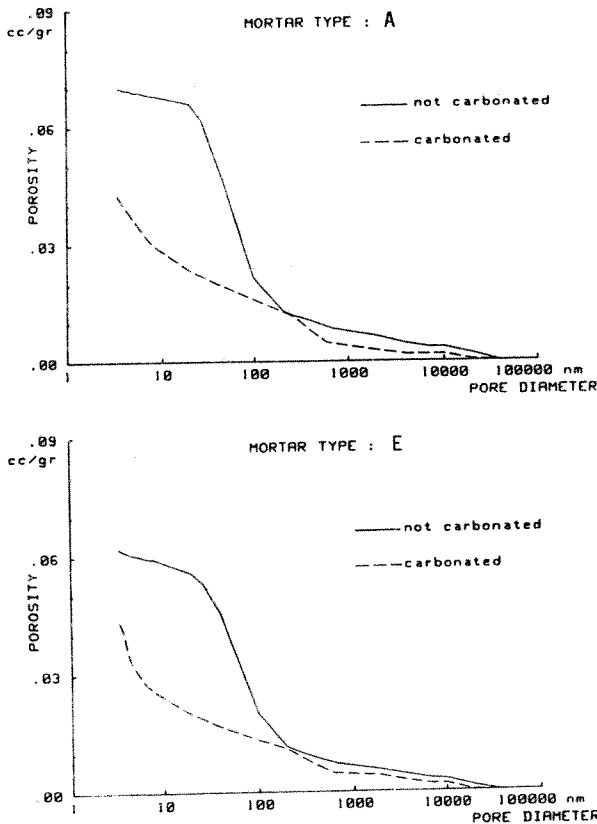


Fig. 3 : Pore size distribution for not carbonated and carbonated mortars.

4. RESULTS

Experimental results described in section 3 can be used directly in the analytical model of section 2. So far our own experimental results are not yet complete. Therefore some of the parameters in the model had to be taken from the literature and others had to be introduced as an "educated guess". The final aim of this project is, however, to determine all parameters needed with sufficient accuracy.

A numerical solution of the set of three equations given in section 2 allows us to determine the moisture distribution of a drying specimen as well as the depth of the carbonated layer. Two examples have been run. One represents a standard quality concrete (C1) and the other is typical for a poor concrete (C2). The coefficient of diffusion of CO₂ DG has been increased by a factor of 10 in the case of the "poor quality concrete" C2. The processes near the surface are graphically represented in Fig. 4 for C1 and in Fig. 5 for C2. For the "standard concrete" the moisture distribution within a layer of a thickness of 10 mm is shown after 1, 10, 100, and 1000 days respectively. In addition the depth of carbonation is indicated for identical intervals. In the case of the "poor quality concrete" the surface layer has been chosen to be 15 mm. In Fig. 6 the calculated depth of carbonation is replotted as function of time. For comparison experimental results observed on different types of concrete have been taken from Schiessl /8/ and have been introduced in Fig. 6.

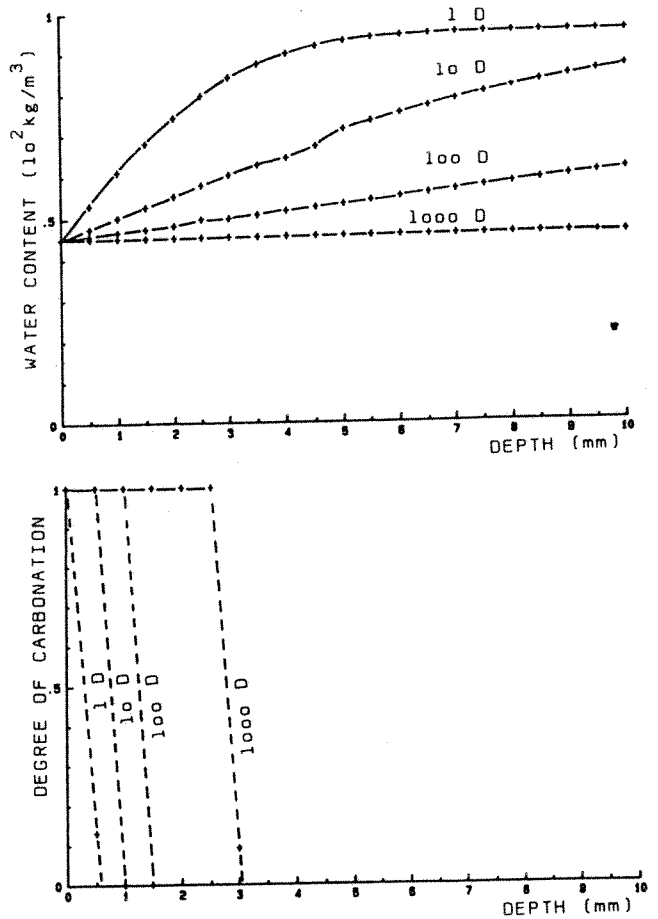


Fig. 4 : Moisture distribution and depth of carbonation in the surface layer of a "standard concrete". The time is indicated as parameter in days.

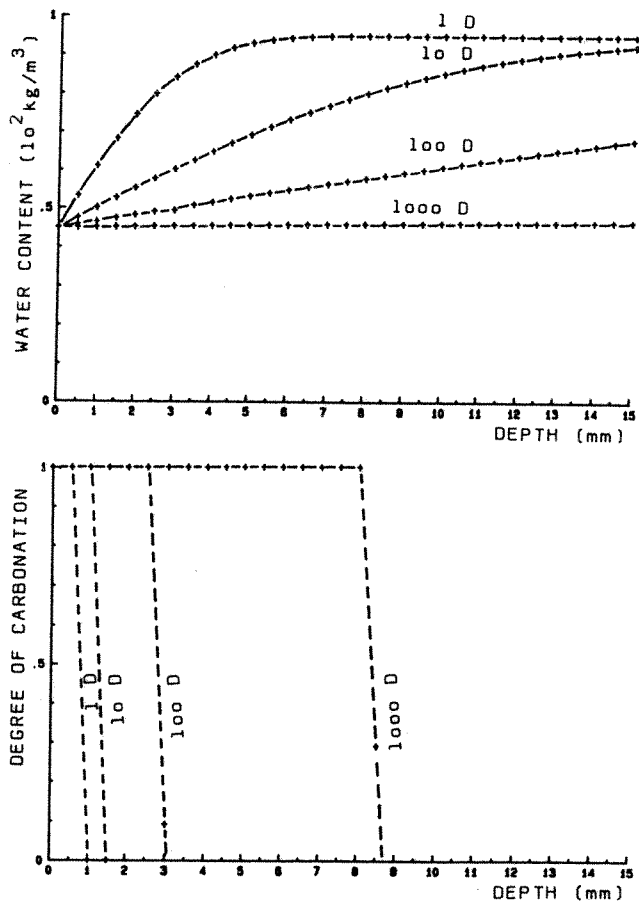


Fig. 5 : Moisture distribution and depth of carbonation in the surface layer of a poor quality concrete. The time is indicated as parameter in days.

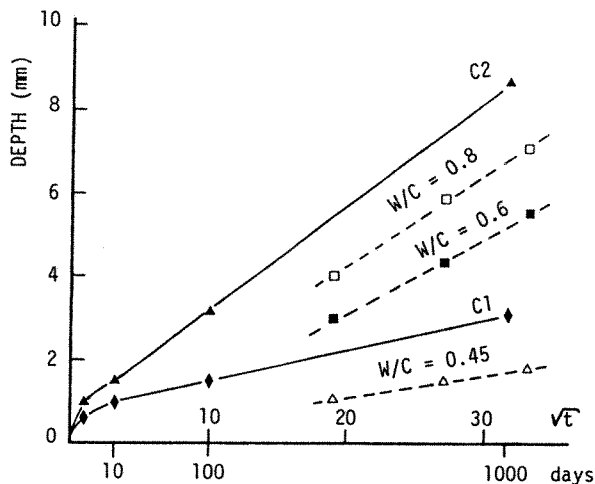


Fig. 6 : Depth of carbonation as function of time as calculated for two "types of concrete". For comparison experimental results taken from Schiessl /8/ are shown.

5. DISCUSSION AND CONCLUSIONS

In principle all important influences on rate of carbonation can be taken into consideration by the model suggested in this contribution. In this way interesting parameter studies can be carried out. Not all necessary data, however, are available nowadays. It has to be mentioned at this point that a number of experimental result cannot be obtained easily. Rate of carbonation as function of RH for instance will be difficult to determine experimentally with great accuracy. As the carbonation proceeds the humidity content is changed and thus influences rate of carbonation.

The influence of concrete composition and of degree of hydration on rate of carbonation can be adequately represented by this model. It is possible to predict service life of a concrete element or of a structure under arbitrary climatic conditions. The influence of temperature has been neglected so far but it is possible to introduce it at a later stage.

From Fig. 6 we can learn that after an initial quick carbonation the growth of the thickness of the carbonated layer follows approximately a $(t)^{1/2}$ -law. This result is in agreement with earlier findings. For a rough estimation of the thickness of the carbonated layer after a given time interval t the following simple equation can be used :

$$d = a + b \sqrt{t} \quad (11)$$

This expression has already been suggested on a purely empirical basis by Venuat and Alexandre /9/.

In reality the mean value of the depth of carbonation is of limited value. It is more important to know the probability of occurrence of extreme values. The numerical model can be extended to cover statistical aspects of materials properties as well as of climatic conditions. This possible extension of the model is especially interesting for a realistic reliability assessment.

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