Table 6 Recommended limit value of crack width (w_{max}, mm) in case of reinforced concretes threatened by carbonation according to Eurocode EC2

Type of reinforcement and the conditions of occurrence of the actions	$w_{max,}$ mm for exposure class	
	XC1	XC2, XC3, XC4
Elements prestressed by tendons with bond Frequent combination of actions	0,2	0,2*
Reinforced concrete elements, elements prestressed by tendons without bond Quasi-permanent combination of actions	0,4	0,3

*) provided that they meet the requirements of decompression (ie. each tendon is covered by a layer of compressed concrete of thickness of at least 25 mm)

Taking into consideration above it can be concluded that according to Eurocodes EC0 and EC2 the thickness of the cover in the particular exposure class depends only on the structural class/category and concrete strength class – it is not differentiated for various cements, nor additives, nor technological types of concrete. As a consequence, the selected thickness of concrete cover is in fact a far estimation – sometimes too exaggerated (too safe or too risky).

2. RESEARCH SIGNIFICANCE

This paper contains author's own (Woyciechowski 2013, Czarnecki and Woyciechowski 2012, 2013, 2015, 2016) mathematical model of carbonation. The model defines the carbonation as the process of limited possible range into the concrete and is described by hyperbolic function of time. In the following paragraphs one will find the proposal of use of the model as a tool for determining the minimal thickness of the concrete cover, ensuring the durability of reinforced concrete structure due to the risk of carbonation. There is also given a practical algorithm of elaborating of the model and using it to determine the minimum cover due to carbonation.

The presented model of carbonation progress is different from the traditional models described by parabolic functions that were published worldwide so far (for details see paragraph 3), but it was verified in a wide range of material variables, technological variables as well as environmental variables published in the earlier works of the authors. Meanwhile the given algorithm enables optimal choice of the concrete cover thickness, which minimizes the uncertainty occurring during designing the reinforced concrete structures according to the simplified approach discussed in the first part of this paper.

3. CARBONATION MODELS

3.1 Traditional approach to mathematical model of carbonation

Research on the development of universal models of carbonation, describing its changes in time and taking into account different material and technological variables, has been conducted for many years in various research centers (Bary and Sellier 2004, Burkan et al. 2004, Hossain et al. 2005, Ishida, Maekawa and Soltani 2004, Maekawa and Ishida 2002, Loo et al. 1994, Masuda and Tanano 1991, Ming Te Liang et al. 2002, Monteiro et al. 2012, Steffens et al. 2002, Papadakis 1991, Muntean 2009). In mathematical modeling of carbonation a key issue is to determine the intensity of carbon dioxide flow through concrete. The starting point is the first Fick's law, which allows to describe the diffusion process under a constant density of the diffusion flux. Final result of carbonation modeling is power function of carbonation depth in time, expressed in the form:

$$x = \sqrt{\frac{2D\varphi_{ext}}{a}} \cdot \sqrt{t} \tag{1}$$

where: x – depth of carbonation; D – diffusion coefficient; φ_{ext}– external concentration of CO_2; t – time of carbonation; a – coefficient determining the amount of CO_2 bound in the way of carbonation by unit volume of concrete in kg/m^3, calculated acc. to the CEB Bulletin 238 (1997) as: a=0,75·C·[CaO]·αH·(M_{CO2}/M_{CaO}) (C – content of cement in concrete, kg/m^3; [CaO] – CaO content in the cement composition; αH – degree of hydration of cement; M_{CO2}, M_{CaO} – molar masses).
In practice, the most widely used model is greatly simplified. It relates to an average constant RH and carbon dioxide concentration in the environment and can be expressed in the form:

$$x = A \cdot t^{1/2} + B \tag{2}$$

where A is a constant depending on the diffusion coefficient, the ability of concrete to bind CO_2 and CO_2 concentration in the air, whereas B is an empirical factor accounting the initiation period of carbonation. This model is used by most researchers, for example Bary and Sellier (2004), Burkan et al. (2004), Hossain et al. (2005), Ishida, Maekawa and Soltani (2004), Maekawa and Ishida (2002), Loo et al. (1994), Masuda and Tanano (1991), Ming Te Liang et al. (2002), Monteiro et al. (2012), Steffens et al. (2002), Papadakis (1991) or Muntean (2009) as a basic model that determines the depth of carbonation, x after the time of exposure, t.

3.2 Model of carbonation as the finite process

The abovementioned models treat the phenomenon of carbonation as process occurring due to the exposure in environment containing carbon dioxide unlimited in concrete space and unlimited in time. It is assumed that the end of carbonation is related only to the exhaustion of reagents available in the system, including mainly $Ca(OH)_2$ and in the further horizon other hydrates. However, an important issue is the accessibility of CO_2 into the system, especially, in the deeper layers of concrete. Diffusion of CO_2 resulting from the concentration difference in the way from the surface into the concrete depends not only on the concentration gradient but also on the concrete microstructure. The described models based on the first Fick`s law assume that the medium in which diffusion takes place will not change over time, which allows the reception of a constant diffusion flux in the equation (1). This is a significant simplification of carbonation process description, which does not take into account a number of additional factors, such as changes in diffusivity as a function of humidity, changes in atmospheric concentrations of CO_2 in climatic year, participation in the carbonation of CSH phase and residuals of non-hydrated cement, qualitative and quantitative characteristics of the material composition of concrete (w/c, type of cement, additives, admixtures, aggregates size and content), technological and environmental factors (curing, temperature, state of stress) and, first of all, diffusivity changes resulting from changes in time of the concrete microstructure. The latter effect, resulting from the saturation of the pores with carbonation products, limits the possibility of a direct description of a process based on Fick's law. The result of carbonation is a decrease in porosity, in particular capillarity that takes place in addition to the occurrence of carbonation shrinkage, thus reducing the permeability of the concrete and therefore the possibility of diffusion of gases in concrete. This nature of the phenomenon was mentioned for the first time by Bakker in 1988, (Bakker 1988) and later by Hergenröder (1992), Nilsson (1996) and Fagerlund (1997). Such approach to the carbonation phenomenon was further developed in the Department of Building Materials Engineering on Warsaw University of Technology under the guidance of Czarnecki and results were widely published (Czarnecki and Więcławski 2003, Woyciechowski 2013, Czarnacki and Woyciechowski 2012, 2013, 2015, 2016, 2012, Czarnecki and Sokołowska 2015).

Abovementioned works conclude that concrete carbonation in urban-industrial conditions can be described with a hyperbolic function of carbonation depth in time (reciprocal square root of time), which has asymptotic value parallel to time axis. This asymptote is a limit of carbonation depth. Traditional and hyperbolic models of carbonation are shown on Fig. 1.

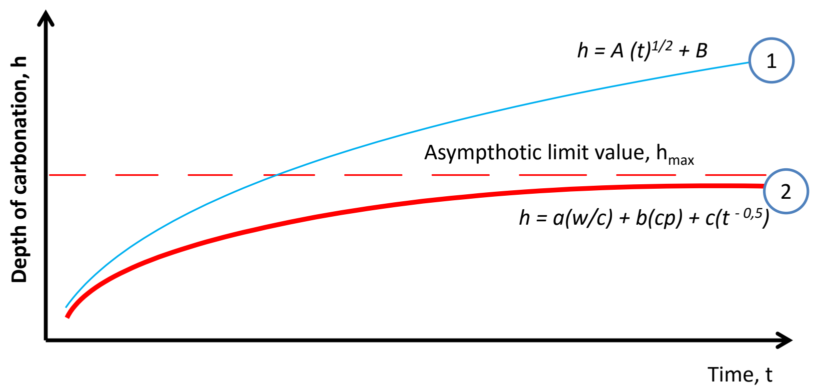

Fig. 1 “Traditional” power (1) and hyperbolic (2) models of carbonation phenomena

The hyperbolic carbonation model is expressed in the form:

$$h = a(w/c) + b(t_{ec}) + c(t^{-0,5}) \qquad (3)$$

where: h – depth of carbonation, mm, w/c – water-cement ratio, t_{ec} – early curing time, days, t – time of exposition, years, a, b, c – coefficients describing relevance of influence of w/c ratio, early curing and exposition time on depth of carbonation. It was stated that parameters (a, b, c) mainly depend on binder properties, presence of mineral additives and, especially, on CO_2 concentration. Similar models were elaborated for different types of concrete, particularly with use of Portland cement and cement incorporating slag and fly ash. SEM analysis shows different density of