Lietuvos statybininkų asociacija

STATYBINĖS KONSTRUKCIJOS IR TECHNOLOGIJOS
ENGINEERING STRUCTURES AND TECHNOLOGIES
ISSN 2029-2317 print / ISSN 2029-2325 online
2011 3(2): 51–55
doi:10.3846/skt.2011.06

ACCELERATED CARBONATION DEPTH TEST IN AN ATMOSPHERE OF 98% CO_2

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Received 2011 03 10; accepted 2010 04 21

Abstract. The action of atmospheric carbon dioxide is one of the agents which substantially reduce the durability of concrete structures. This so called carbonation is one of the corrosive processes influencing properties of mature concrete. It is caused by a chemical reaction of carbon dioxide infiltrating into the surface of a concrete construction with the minerals of cementing compound. The effect of carbonation can be evaluated by means of the "accelerated carbonation depth test in 98% CO_2". The principle of this method consists in finding a correlation dependence of "depth (or time) of carbonation in the natural environment / depth (or time) of carbonation in the accelerated test". The theoretical carbonation depth of common concrete placed in the natural environment of 0.03% CO_2 for a long time can be determined from the Fick's law. The actual carbonation depth of common concrete placed in 98% CO_2 can be determined by a simple phenolphthalein test on fresh fragments of standard concrete samples. The correlation dependence found in the so-called "accelerated test" enables us to determine intervals of real time in the natural environment of 0.03% CO_2 corresponding to the intervals of accelerated exposition in 98% CO_2.

Keywords: carbonation, acceleration of carbonation, diffusion, phenolphthalein test, 98% CO_2, correlation.

1. Introduction

One of the most observed quality characteristics of building constructions and materials today is their lifetime (Šmerda *et al.* 1999; Pytlík 2000). The actual lifetime prolongation is desirable from both the economic point of view, and the point of view of saving the unrenewable resources of raw materials. In the case of a planned construction, we can markedly influence lifetime by the right choice of materials or their combinations, or by adjusting formulations and input materials (Šauman 1965; Vavřín, Retzl 1987). In the existing structures we can extend maintenance intervals or total lifetime by the right choice of preservatives (Kamaitis 2009). Degradation of building materials can occur from the inside (e.g. loss of strength of aluminous cements, alkaline aggregate reaction in concretes), but more often from the outside as a result of surrounding aggressive environment (Schiessl 1976). The most observed effect nowadays is the degrading effect of gaseous CO_2 present in the atmosphere on the properties of mastic cement – the so-called carbonation of concrete (Bob, Afana 1993; Dhir *et al.* 1989; Houst, Wittmann 2002). This carbonation of mature concrete is caused by a chemical reaction between carbon dioxide diffusing into the surface of a concrete structure and the minerals of mastic cement – predominantly calcium hydroxide $Ca(OH)_2$ (Matoušek, Drochytka 1998). The air usually contains approx. 0.03% of CO_2, in the industrial zones this concentration can be many times higher. Carbon dioxide is 1.53 times heavier than air and that is why it remains near the ground if undisturbed. Outside, however, where the wind moves the air, its level increases highly. This can be observed in some relatively high bridges and other structures examined in samples taken from them showing a certain evident degree of carbonation.

Matoušek and Drochytka (1998) mention four stages of carbonation altogether. In the **first stage**, carbon dioxide penetrates into the surface pores of concrete and reacts with calcium hydroxide to form calcium carbonate ($CaCO_3$) according to the equation

$$Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2\,H_2O. \qquad (1)$$

The resulting calcium carbonate crystallizes in the pores and increases its volume. This calcium carbonate lowers significantly concrete permeability and it is at the same time far less soluble than the original calcium hydroxide. On the surface of a concrete structure a solid layer appears which propagates in the course of time and simultaneously, the pH value of concrete, which successfully ensured passivation of steel reinforcement before this input, decreases (Keršner *et al.* 2004). This decrease in steel passivation is in fact the worst impact of carbonation in steel reinforced concrete.

The **second stage** is mainly characterized by changes of other hydration products of mastic cement, moreover, due to the present humidity and CO_2, the resultant $CaCO_3$ is further converted into soluble $Ca(HCO_3)_2$ according to the equation

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 \qquad (2)$$

In the **third stage** of carbonation, the previously originated carbonate formations recrystallize giving rise to very large calcite and aragonite crystals. The **fourth stage** is typical for its almost 100% carbonation. The third and fourth stage of carbonation worsen substantially the strength characteristics of concrete, the pH decreases markedly; the fourth stage can already be a stimulus for the spontaneous destruction of concrete structure.

The presented paper focuses mainly on finding a correlation dependence between the carbonation depth of concretes exposed to the accelerated carbonation test in an atmosphere of 98% CO_2 (see Fig. 1) and between the carbonation depth of concretes exposed to the effects of the internal atmosphere (see Fig. 2) as well as to the external atmosphere.

2. Experimental

The research evaluating the 24-month accelerated carbonation depth test of untreated concrete cubes of 150×150×100 mm in size, was carried out on 8 sets of samples (marked **A, B, C, D, E, F, G** and **H**). The set of cubes **A, B, C, F** and **H** (28-day compression strength of approx. 18 MPa) was tested in 2009, the results of the set of cubes **D, E** and **G** (28-day compression strength of approx. 23 MPa, formulation identical with samples **A** and **F** – see Table 1) from early 2010 supplementing the previous findings. According to ČSN EN 13 295, it is possible to determine the resistance of repair products or systems to carbonation by means of an accelerated laboratory test, in which the test pieces are exposed to an atmosphere containing 1% CO_2 for a period of 56 days. This standard test serves in fact as a sort of initial elimination criterion for the selection of optimum repair mortars or concretes for application to the restored structure. However, it does not say much about the actual depth or extent of damage caused to

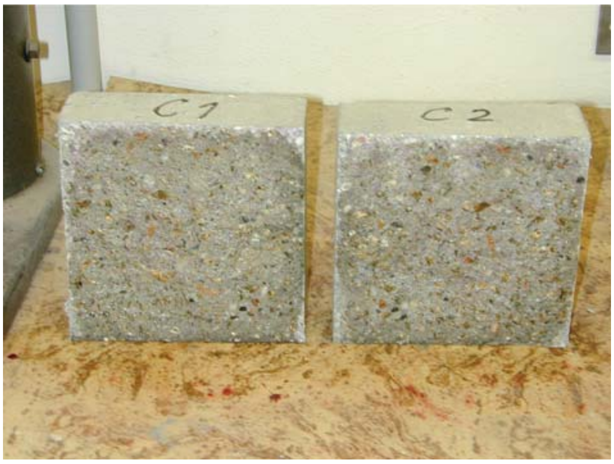

Fig. 1. Sample of formulation C placed in 98% CO_2 for 365 days, carbonation depth 75 mm, real sectional dimensions of sample: 150×150 mm (Scale: 1:5)

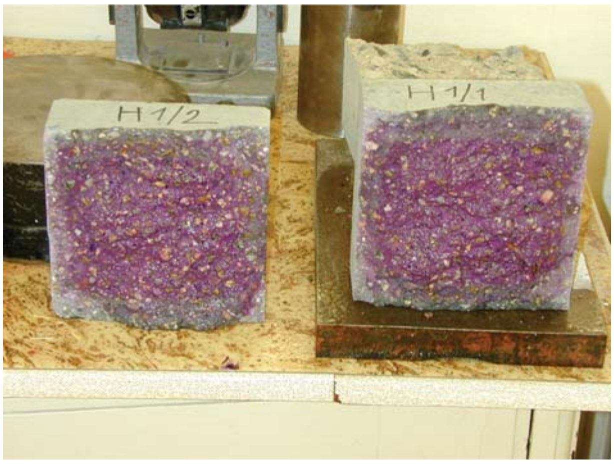

Fig. 2. Sample of formulation H placed in 0.03% CO_2 (internal laboratory environment) for 365 days, average carbonation depth 1mm, real sectional dimensions of sample: 150×150 mm (Scale: 1:5)

Table 1. Concrete mixture composition + compression strength

Formulation for	Unit	A, D, E, F, G, H	B	C
1 m^3				
CEM I 42,5 R	[kg]	350	350	350
Sand 0–4 Tovačov	[kg]	1122	1122	1122
Gravel 4–8 Luleč	[kg]	748	748	748
Crackstop fibres	[kg]	–	0,6	0,9
Plastificator SIKA V 3	[l]	3,5	3,5	3,5
Water	[l]	168	168	168
28-day compres. strength	[MPa]	22,8	15,6	16,1

the structure by carbonation in the middle or at the end of its lifetime (Ismail *et al.* 2010). When deriving the correlation dependence of accelerated time / natural time, it was necessary to compare the real carbonation depth of concretes exposed to the long-lasting effects of the natural atmosphere with the carbonation depth of comparative concretes in an environment of 98% CO_2.

A transition from the standard 1% CO_2 to the 98% CO_2 was called for by accelerating the chemical process of carbonation and by the financial expensiveness of obtaining 1% CO_2 (from Belgium). A problem of the correlation serched here will always be the absence of real pairs of the originally identical concrete samples for the determination of carbonation depth, one of which was (or is) exposed to decades of slow effects of carbonation in the structure and the other one of which undergoes a comparative accelerated test in 98% CO_2.

Carbonation depth of common concrete placed in the natural atmosphere (0.03% CO_2) for a long time can be determined by calculation according to many authors, e.g. Henning and Lach (1983) or Matoušek and Drochytka (1998) or Seng Diep and Šlopková (2000). The relation according to Matoušek and Drochytka (1998) seems to be the most general one, the so-called Fick's law in the following form

$$x = k.\sqrt{t} \qquad (3)$$

which is based on the principle of a constant increase of carbonation depth with time. X indicates the depth of the carbonated layer in mm, t is the time in days and k is the constant ranging from 0.2 to 0.4 (depending on the cement type and the water ratio v/c). It is apparent that the carbonation depth will be, according to the measurements carried out on the standard samples, partially dependent on the quality of concrete (Muntean and Bohm 2009; Roziere *et al.* 2009). It is also interesting that the increase of carbonation depth calculated according to the Fick's law (Matoušek and Drochytka 1998) is roughly corresponding to the carbonation depths found out in poor quality concretes in the course of the one-year measurement. Fig. 3 shows a conventional curve of the increase of carbonation depth derived theoretically from the Fick's law on the one hand and from the one-year practical measurement in an environment of 0.03% CO_2 on the other hand, and simultaneously a growth curve for average concrete (30 MPa in compression) determined by measurement in an environment of 98% CO_2.

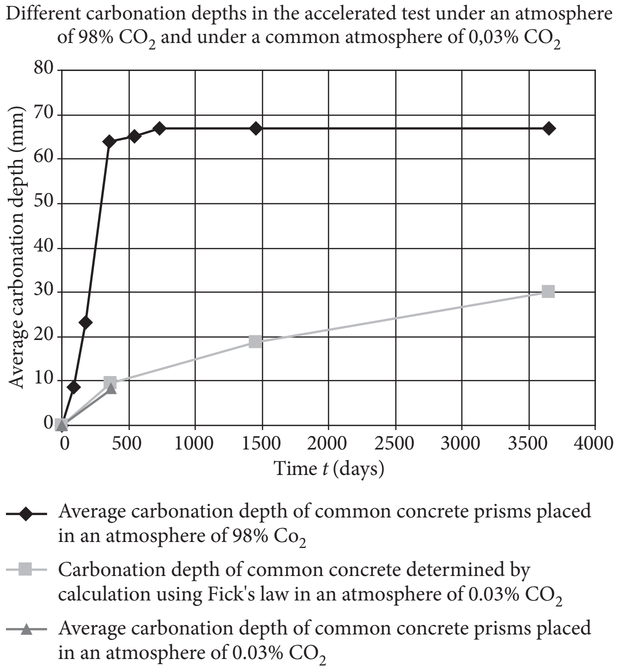

Fig. 3. Different carbonation depths in an atmosphere of 98% CO_2 and in the natural atm

Table 2. Comparison of carbonation times of the identical layers of concrete in the environment of a real atmosphere (0.03% CO_2) and in the highly concentrated environment of 98% CO_2

Carbonation depth (mm)	Atmospheric CO_2 (0.03%) exposure time – T_1 (days)	Concentrated CO_2 (98%) exposure time – T_2 (days)	Ratio T_1 / T_2
5	132	60	2,2
10	520	100	5,2
15	1080	140	7,7
20	1680	160	10,5
25	2700	200	13,5
30	3700	220	16,8

3. Conclusion

It is apparent from the chart in Fig. 4 and from the following Table 2 that the speed of carbonation in an environment of concentrated 98% CO_2 constantly increases in comparison with the natural environment containing 0.03% CO_2. If the carbonation depth measured in the concrete tested in the accelerated test after two months of placement in 98% CO_2 is 10 mm, then the same damage in the real environment of 0.03% CO_2 would occur in 312 days (10.4 months) – see Fig. 4 (Stehlík 2008). However, the dependence between the time of corresponding damage of concretes in the concentrated and natural environments was determined for samples of common concrete with a 28-day strength of approx. 30 MPa.

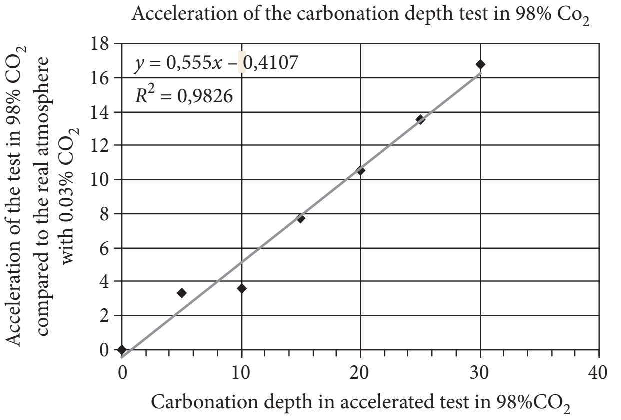

Fig. 4. Acceleration of the carbonation depth test in 98% CO_2

Acknowledgement

This work was supported by Research Project of the Ministry of Education and Youth of the Czech Republic No. VVZ MSM 0021630511 "Progressive Building Materials with Utilization of Secondary Raw Materials and their Impact on Structures Durability".

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PAGREITINTOS KARBONIZACIJOS GYLIO EKSPERIMENTINIAI TYRIMAI 98 % CO_2 ATMOSFEROJE

M. Stehlík

Santrauka. Atmosferoje esančio angies dvideginio (dioksido) poveikis yra vienas iš veiksnių, gerokai mažinančių betono ilgaamžiškumą. Šis procesas vadinamas karbonizacija – tai vienas iš korozijos procesų, turinčių įtakos seno betono savybėms. Koroziją sukelia anglies dvideginio, prasiskverbusio per betono paviršių, reakcija su rišamosiomis medžiagomis. Karbonizacijos įtaka gali būti vertinama pagal pagreitintos karbonizacijos gylio eksperimentinius tyrimus 98 % CO_2 atmosferoje. Šio metodo principas – koreliacinės priklausomybės radimas tarp karbonizacijos gylio (laiko) normalioje aplinkoje ir pagreitintos karbonizacijos gylio (laiko) eksperimentinių tyrimų. Teorinis įprastinio betono, esančio normalioje aplinkoje (0,03 % CO_2), karbonizacijos gylis, atsižvelgiant į laiką, gali būti apskaičiuojamas pagal Ficko (Fick) dėsnį. Aktualus įprastinio betono karbonizacijos gylis, esant 98 % CO_2 aplinkoje, gali būti apskaičiuojamas atliekant paprastus fenolftaleino eksperimentinius tyrimus su standartiniais betono bandiniais. Rastoji koreliacinė priklausomybė tarp vadinamosios pagreitintos karbonizacijos leidžia apskaičiuoti betono, esančio normalioje aplinkoje (0,03 % CO_2), realaus laiko intervalus, atitinkančius realaus laiko intervalus betono, esančio 98 % CO_2 aplinkoje.

Reikšminiai žodžiai: karbonizacija, pagreitinta karbonizacija, difuzija, fenolftaleino tyrimai, 98 % CO_2, koreliacija.

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